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CONTROL OF FRETTING FATIGUE

# Control of Fretting Fatigue



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Commission on Sociotechnical Systems

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The state of the art of fretting and available fretting-initiated fatigue tests are assessed. Recommendations focus on a program of research designed to improve understanding of fretting-initiated fatigue mechanisms and on aspects of evaluation. Guidelines for use by designers to circumvent the development of fretting also are described. An extensive review of the literature is included as is a 210-item bibliography.

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# CONTROL OF FRETTING FATIGUE

Report of

THE COMMITTEE ON CONTROL OF
FRETTING-INITIATED FATIGUE

NATIONAL MATERIALS ADVISORY BOARD
Commission on Sociotechnical Systems
National Research Council

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1977

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This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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## PREFACE

The authors have given generously of their resources of knowledge and time in preparing this report. Credit is given to R. C. Bill, R. L. Johnson, and G. M. Sinclair who provided drafts on the Literature Appraisal and the Bibliography; to C. Albrecht and L. B. Wehle on Problem Definition; to E. Rabinowicz and C. H. Wells on Fundamentals; to J. A. Collins, D. W. Hoeppner and C. N. Rowe on Design Approaches; and to R. C. Bill and G. M. Sinclair on Evaluation Methods. Dr. Frederick F. Ling, Chairman of the Committee managed and coordinated the preparation of this report.

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# ABSTRACT

The state of the art of fretting and available fretting-initiated fatigue tests are assessed. Recommendations focus on a program of research designed to improve understanding of fretting-initiated fatigue mechanisms and on aspects of evaluation. Guidelines for use by designers to circumvent the development of fretting also are described. An extensive review of the literature is included as is a 210-item bibliography.

## EXECUTIVE SUMMARY

### A. INTRODUCTION

This study was undertaken by the Committee on Control of Fretting-Initiated Fatigue of the National Materials Advisory Board to examine the state of knowledge of fretting and particularly the fatigue consequences in order to:

- Propose a program to improve the understanding of fretting-initiated fatigue mechanisms.
- Provide standards of tolerable limits of damage (which proved to be beyond our knowledge and capability).
- Assess available fretting-initiated fatigue tests.
- Review available guidelines for the use of designers to circumvent the development of fretting.

#### 1. Fundamentals

There are three widely accepted progressive stages of fretting: (a) the initial adhesion and metal transfer; (b) the production of debris in a reactive state; and (c) the steady-state wear condition that can be adhesive, abrasive, corrosive and fatigue. The geometry of the fretting part and the properties of the debris have much to do with the manner in which steady-state wear condition progresses.

Fretting fatigue cracks usually originate in surface pits. Pits are formed in the early stages of wear by rupture of adhesive contacts between asperities, which may itself be a fatigue mechanism, with microcracks propagating roughly parallel to the surface. This process may be aided by oxidation or corrosion, possibly catalyzed by the wear mechanism itself. The process is inhomogeneous and strongly dependent on surface finish. The possibility of corrosion pitting occurring later in the wear process by galvanic action or formation of acid environment exists.

The coefficient of friction is determined by the environment, amplitude of relative slip and the properties of the material. The coefficient of friction,

along with the geometry of the contacting surfaces and the loading between them, governs the stress distribution that determines the rate of fatigue crack growth, if any, from surface defects, and the depth at which these cracks may be arrested. The prediction of crack growth is tractable by fracture mechanics under most environmental conditions; however, identification of the local chemical composition in the contact area is usually not possible.

A myriad of approaches against fretting-initiated fatigue have been suggested and used for the selection of materials, surface films, lubrication and mechanical solutions. It is very likely that such a wide variety of conditions and applications indicates the need for a systems analysis approach to resolve the differences in successes with these different means for mitigating fretting fatigue.

## 2. Test Equipment

Little detailed information is available on the devices that are used as test equipment. It is very clear that the experimental devices showing attractive applicability involve imposing the fretting test onto a typical fatigue experiment. Standardization of a test is needed to permit interlaboratory comparisons. Tension fatigue specimens are most commonly used. Bending fatigue specimens have also been employed, but these introduce some problems in defining the contact area of the fretting components. However, there are many cases where bending fatigue probably more closely approximates the application than straight tension experiments.

## 3. Design Against Fretting-Initiated Fatigue

Two design procedures are discussed in Chapter 3. Fail safe design is a process that considers the damage tolerance of the material and the structure together. Inspection intervals are set so that damage can be detected and repaired before complete failure occurs. A different concept of predicting safe life based on crack size and crack growth rates (fracture mechanics) can alternatively be used. In either case, the significant decision is the selection of an acceptable stress level. A scientific basis for predicting the occurrence of fretting does not exist; engineering experience is necessary to anticipate the problem. Contrary to evaluating some other mechanisms, it is necessary to conduct rather complex tests on built-up structures to adequately simulate service behavior which can lead to fretting damage, and thus to subsequent fatigue failure. Once a fretting problem is revealed, there are a number of approaches (see pages 34-36) that can be taken to minimize or prevent it.

## B. RECOMMENDATIONS

### 1. Fundamentals

#### a. Metals

An effective program of research should include a study of fatigue-life degradation with associated inquiries concerning crack propagation, trajectory of propagation and crack length measurement. Material parameters should include texture, grain size and structure, cold work and crystallographic orientations. Contact stresses and microslips associated with given geometries and material pair should be quantitatively understood. The effect of surface roughness should be included. Moreover, the effect of environment is crucial in the studies.

#### b. Coatings

As coatings are used to mitigate fretting-initiated fatigue, their wear or degradation is of interest. Modes of wear include spallation, plastic displacement and cracking. Studies should include metallic, ceramic and intermetallic systems.

#### c. Liquid and Grease Lubricants

As liquid and grease lubricants are used as inhibitors of fretting-initiated fatigue, the mechanisms by which these agents render their function should be studied.

### 2. Evaluation

#### a. Fretting-Fatigue Conditions

It is most important to have the test surfaces exposed to fretting and fatigue simultaneously. The importance of experimental geometry cannot be overstated. For example, the regime of nominal slip (the slip is nonuniform over the contact area) must be considered. It is also necessary that the amplitude control be made independent of the stress level control. Among the quantities to be measured, the relationship between fretting wear and fatigue crack initiation should be identified. It must be recognized that a test device to simulate operating conditions will not be optimum for elucidating basic mechanisms, and vice versa.

b. Coatings

Coatings should be evaluated in a systematic fashion based on coating wear studies in which friction is also measured.

c. Prototype

Testing of prototypes must encompass all of the above criteria.

## CHAPTER 1

## PROBLEM IDENTIFICATION

### A. DEFINITION OF TERMS

The nature of fretting-induced fatigue is not understood by many people. The terms used to describe the phenomena are not universal.

Since terms such as fretting, fretting-initiated fatigue, and component failure mean various things to different people, these will be defined for the purposes of uniformity in this report.

#### 1. Fretting

Fretting is a surface damage phenomenon occurring on two contacting surfaces having oscillatory relative motion of small amplitude. Some other more specific fretting terms used in relation to fretting are:

- Fretting Corrosion. A form of fretting damage including corrosive chemical reactions at the fretting interface.
- Fretting Wear. A form of surface damage resulting in a measurable loss of material from the interface as wear particles.

#### 2. Fretting-Initiated Fatigue

A condition where the material fatigue strength is degraded by the presence of the following:

- Surface stress concentrations resulting at sites of fretting pits.
- Surface and subsurface stresses resulting from rubbing friction contact combined with the stresses resulting from the overall fluctuating stress field.

#### 3. Component Failure

Component failure is the inability of a component to sustain design loads or to properly perform the intended function.

## B. PROBLEM DEFINITION - GENERAL

Fretting can eventually result in component failure (part does not perform function) in any of the following modes:

### 1. Fatigue Failure

Fretting-initiated cracks present in components subjected to a fluctuating stress environment can continue to grow until complete structural failure occurs.

The crack growth characteristics are amenable to analysis *if* the stress environment can be defined. For most mechanical components, the vibratory stress environment is complex and not easily defined. Accurate crack growth prediction may not be possible and, therefore, fretting-initiated cracks cannot be tolerated.

### 2. Static Failure

Existing fretting-initiated cracks that are of sufficient size to exceed the critical stress intensity factor can be the cause of subsequent static rupture.

### 3. No Structural Failure

Fretting, occurring between surfaces that are occasionally subjected to large motions, may increase the frictional resistance to the point of complete seizure. If the resistance cannot be overcome, the part cannot properly perform its function.

Since in many cases (but not all) fretting can result in premature component failure or the loss of ability to perform adequately, corrective measures quite frequently taken are:

- Minimize the fretting by optimizing the parameters affecting fretting and, thereby, providing adequate life prior to component retirement. Examples are:

  (a) Introduction of interface coatings
  (b) Improved surface lubrication
  (c) Increased fits and pressures
  (d) Use of debris removal techniques
  (e) Shot peening
  (f) Improved surface finish and hardness
  (g) Improved environmental protection

- Design modification to accommodate fretting-induced cracks so that crack propagation and subsequent failure cannot occur.

- Redesign to eliminate fretting surfaces.

## C. PROBLEM DEFINITION - SPECIFIC

### 1. Problem Areas

Fretting problems are generally found in nearly all mechanical components used in any of the following equipment:

- Helicopters
- Fixed-wing aircraft
- Trains
- Ships
- Automobiles
- Farm machinery
- Engines
- Construction equipment

### 2. Drive Systems (example)

#### a. Engines (Turbines)

Fretting is particularly aggravated because of high frequency, low amplitude vibratory motions. Fretting problems are typically encountered in the following areas:

- Blade-to-disk attachments
- Disk-to-disk joints
- Disk-to-shaft joints
- Shaft-to-shaft joints
- Splines

#### b. Transmissions

Fretting is particularly aggravated because of rotating components resulting in cyclic stresses and motions. Fretting problems are typically encountered in the following areas:

- Bearings (oscillating)
- Bearing race/housing interface

- Gear/shaft interface joints
- Splines
- Press-fit joints
- Case/case interface joints
- Bolted connections
- Linkages (pin joints)

c. Shafting

Fretting is aggravated because of rotating components resulting in cyclic stresses and motions. Fretting problems are typically encountered in the following areas:

- Bolted/riveted joint interface
- Gear coupling teeth
- Flex coupling/adapter flange interface
- Adapter/shaft interface
- Universal joints

d. Prime Mover

The prime mover could be a motor, a pump, a rotor (helicopter), wheels (automotive), a generator, etc. All contain bearings and mounting joints. All are, therefore, open to the possibility of fretting.

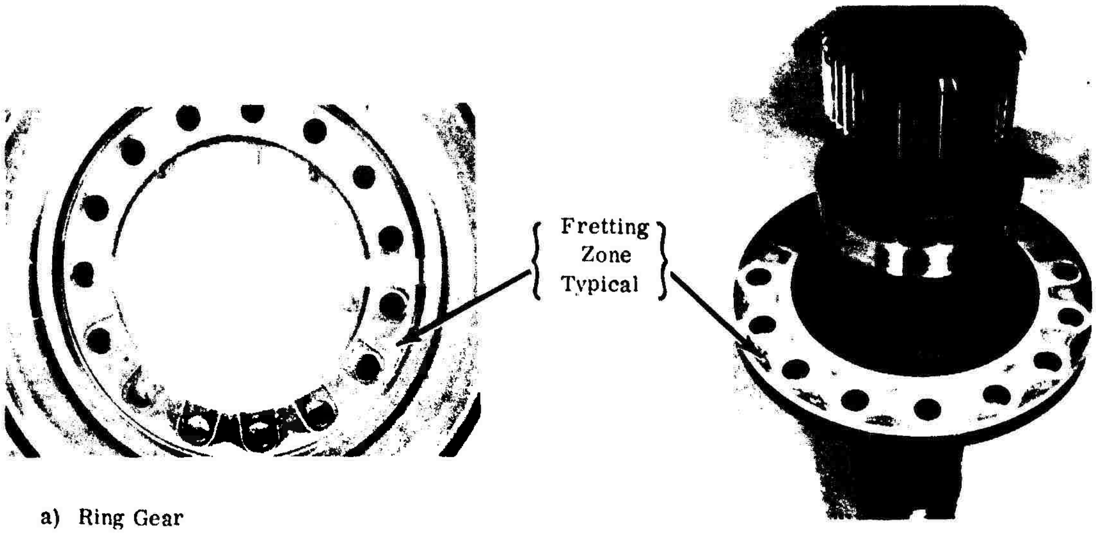
e. Example

Fretting inevitably causes fretting cracks which can propagate and cause component failure. Figure 1 illustrates the fretting pattern evident on the mating halves of a bolted gear/shaft assembly. Figure 2 shows a close-up view of the fretted area in the vicinity of one of the bolted joints. Figure 3 displays a fatigue crack developing from the contact area within the fretted zone. A 200 X enlargement of a cut taken through the crack clearly exhibiting a fretting "spike" is shown in Figure 4. Figure 5 indicates how a crack can propagate from a fretting "spike" and progress around the gear flange until a final failure occurs.

3. Airframes (example)

a. Characteristic Conditions

Characteristic conditions which affect fretting of airframes include:




a) Ring Gear

b) Mating Gear Shaft

FIGURE 1 Typical Fretting Zone

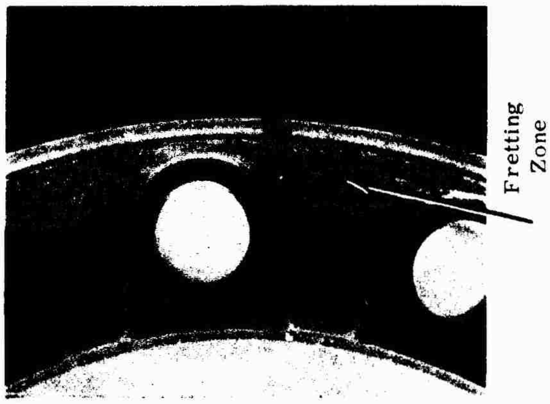



FIGURE 2 Detail of Fretted Zone

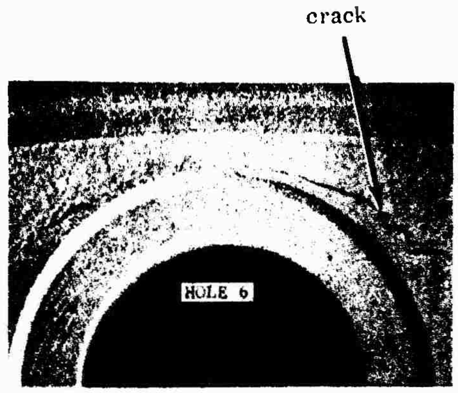



FIGURE 3 Fretted Zone That Has Been Vapor Blasted to Clearly Show Crack

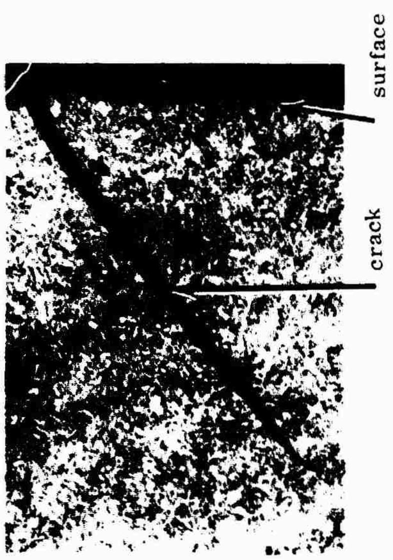



FIGURE 4 200 x Transverse Section Showing Transgranular Fretting Crack

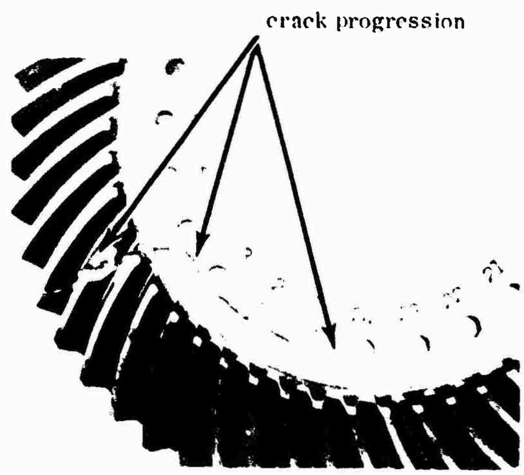



FIGURE 5 Gear Section Showing Crack Progression to Failure

- Load spectrum: large range of load levels resulting from manuevers, atmospheric turbulence, aerodynamic buffet, control surface buzz and incipient flutter, engine vibration, landing ground contact, arrestment and taxiing.

- Spectral distribution depends strongly on location within the airframe.

- Weight optimization leads to high stress fields with relative motion between mating parts.

- Environmental factors include temperature extremes, humidity extremes, grit, salt, corrosive fluids and vacuum (for spacecraft).

- Normal forces exist due to fastener clamp-up, bushing or fastener press fit, as well as operational loads.

b. Hardware Elements

Hardware elements vulnerable to fretting are:

- Structure

  - multifastener lap joints: e.g., wing pivot attachment to center section, beam cap scarf join

  - single-pin joints: e.g., attachment lugs, structural links

  - press fit problems: e.g., bushings in lugs, bearings in housings, fasteners in covers and webs

  - nonstructural interfaces: e.g., breather joints, door and fairing attachments.

- Controls and mechanisms

  - lugs at rod ends, horns and cranks, where bearings and bushings are pressed in

  - attachment of terminal to rod or cable by fasteners or swaging.

# CHAPTER 2

# FUNDAMENTALS OF FRETTING FATIGUE

## A. INTRODUCTION

This chapter examines the current theories and evidence concerning the basic micromechanical and electrochemical mechanisms of crack initiation and growth under fretting conditions.

For convenience of discussion, the phenomena which comprise the problem of fretting can be characterized as follows:

- Mechanical effects, including the state of stress, the irreversibility of inelastic deformation leading to the initiation of fatigue cracks and the fracture mechanics of crack propagation;

- Tribological effects, dealing with the behavior of contact asperities, the coefficient of friction and the generation and distribution of wear product on the faying surfaces; and

- Chemical effects, involving the reaction of the faying surfaces and wear product with the environment, as well as the accompanying modification of the environment, and including the conventionally recognized effects on fracture such as stress corrosion cracking, corrosion fatigue, and hydrogen embrittlement.

The interactions among these phenomena are of particular interest in this review, and it is the committee's objective to identify those interactions that are known, or can be reasonably expected, to govern fatigue fracture.

Several recent reviews have concluded that fretting fatigue cracking, as distinguished from fretting wear, is the result of conventionally accepted fatigue mechanisms and that the tribological and chemical effects enter the process primarily through modification of the macroscopic stress range and its gradient, although fretting-induced pitting may provide the initiation sites for cracking. Indeed, before the significance of the additional effects of wear and corrosion can be evaluated, it is important to understand the state of stress and its effect on crack initiation and propagation; otherwise a simple change in the mechanical response of the specimen can be misconstrued, for example, as an environmental effect. It is precisely this complexity of the mechanical response that has confused the subject of fretting fatigue.

## B. STRESS ANALYSIS OF FRETTING CONTACT

The analysis of even the simplest fretting fatigue laboratory test presents a mixed boundary value problem in which the deformation of the two bodies in contact governs the distribution of boundary tractions and the relative slip. Generally speaking, laboratory tests are designed such that net tangential cyclic displacement occurs between the specimen surface and a contact pad, while structures most often exhibit regions of cyclic slip bounded by regions of no slip. Crack initiation has been observed both at the boundary between slip and unslipped regions and at the outer boundary of a contact surface or wear scar. Both locations have been identified with peak values of surface stress.

The simplest analytical problem is the torsion of a rigid hub press-fit or shrunk onto a circular shaft, Figure 6. Torsion does not alter the radial pressure, and the friction stress may be assumed constant over the slipped area. This example exhibits some generic aspects of the cyclic contact problem:

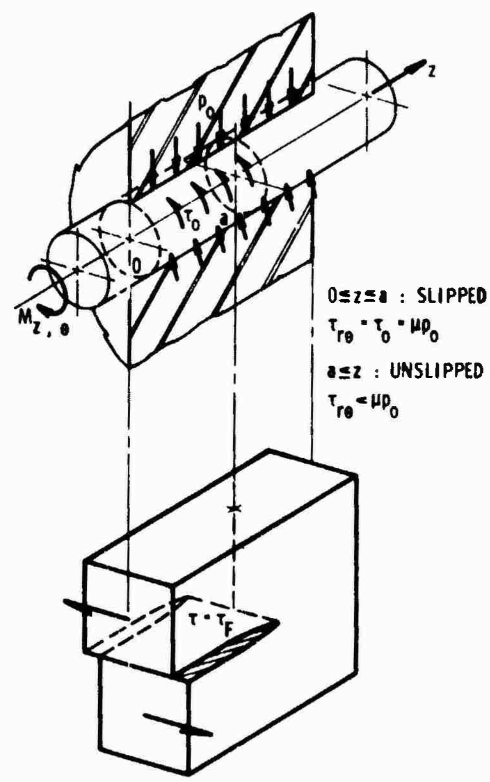



FIGURE 6 Torsion of a Shaft-Hub Assembly

(1) the nonlinearity associated with propagation of the area of slip, which is analogous to the problem of an inverted pileup of dislocations [Bilby, et al. (22)];*

(2) the decay of torsional stress in the shaft governed by the torsional rigidity; and

(3) the development of residual stress, or Bauschinger effect, on unloading.

Obviously, in this simple case, the maximum range of stress in the shaft ($\Delta\tau_{r\theta} = 2 M_z C/J$; $\Delta\tau_{r\varepsilon} = 2\mu p$) occurs at the end of the contact area and not at the slip-no-slip boundary. The complete solution for the cyclic response of this problem is not available, although it involves the minimum degree of nonlinearity.

Other contact problems may be equivalent, analytically, to inelastic fracture mechanics problems. For example, if the hub in the first problem contains a length over which there is no radial pressure, the propagation of slip is equivalent to the model of Bilby, et al. (22) as shown in Figure 7. Finally, if part of the hub is rigidly bonded to the shaft, the problem is equivalent to a Mode III crack in an elastic body with the superposition of a friction

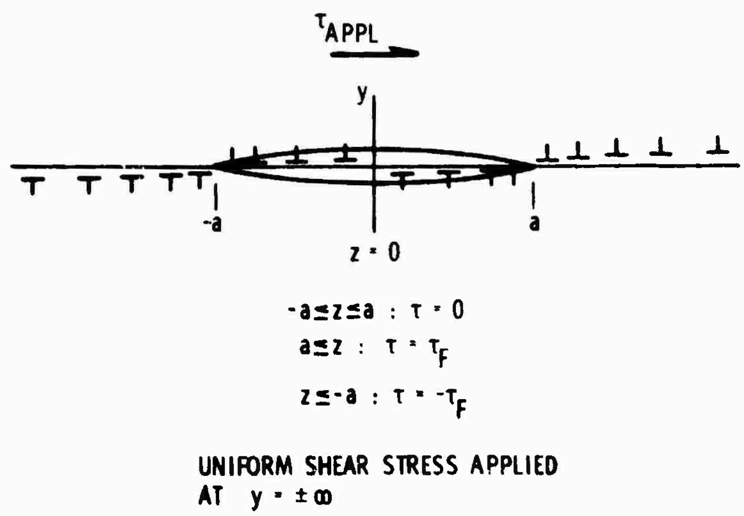



FIGURE 7 Bilby-Cottrell-Swinden Dislocation Model of a Shear Crack. After (22). Reproduced by permission of The Royal Society.

* Numbers refer to entries in the Bibliography.

stress on the crack plane. In this case the maximum stress, which contains a singularity, is developed at the slip-no-slip boundary, rather than at the end of the hub.

The analytical problem becomes more complex if the normal force across the faying surface changes with load. The change may be in phase with the applied load if it is statically determinate or related to elastic deformation of the bodies in contact; it may be out of phase if thermal strains or large variations of mean load are present. As with all nonlinear structural problems, an incremental, finite-element analysis is required to calculate the development of slip displacements, boundary tractions and stress distributions in the two bodies during the first half cycle of loading; general purpose computer programs contain special boundary and crack tip elements for this analysis. However, the solution is required for the ranges of displacements and stress components over a fatigue cycle, and this requirement raises additional complications. First, the criterion for reversed slip is that the boundary tangential traction exceeds the friction stress opposing the displacement. Obviously, since certain joints are known to seize, this criterion may not be met, especially if the loading is not fully reversed. Second, the reversed loading may be unstable.* These problems have not been extensively explored, except in connection with interfacial damping of fatigue displacements. No conceptual difficulty (albeit considerable extra bookkeeping) should be encountered in specifying a dependence of the coefficient of friction on surface traction, slip amplitude, etc., or even in simulating the wear process (decrease in the dimension of the surface element normal to the boundary as a function of relative slip).

The speed and flexibility of finite element analysis, especially for two-dimensional problems, strongly recommend their application to fretting situations, even if cyclic loading is not simulated. Practical problems yield valuable insight, for example, into the effect of manufacturing tolerance, type of lubricant, faying surface contour, etc., on the location and magnitude of peak stress components and their gradients below the surface.

Finite element calculations have been performed for fretting conditions by Bramhall (28) and by Wright and O'Connor (202). According to O'Connor (li), finite element analysis predicted the location of crack initiation on the fretted surfaces of specimens of Al-4% Cu alloy loaded axially or in bending and the calculated S-N results agreed reasonably well with those from plain specimen tests.

Other analyses of contact stress generally follow the Hertz theory for the distribution of normal pressure on a cylindrical contact. Smith and Liu (161),

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* Instability is also associated with the transition from static to dynamic friction. However, it is appropriate to note here that such effects are minimal during continuous cyclic loading.

Nishioka and Hirakawa (123, 124) and O'Connor (li) have determined the distribution of stress for combined normal and tangential loading, with the result shown in Figure 8. The shape of this distribution was confirmed by Roberts (146) by photoelastic analysis. Nishioka and Hirakawa (123, 124) were able to

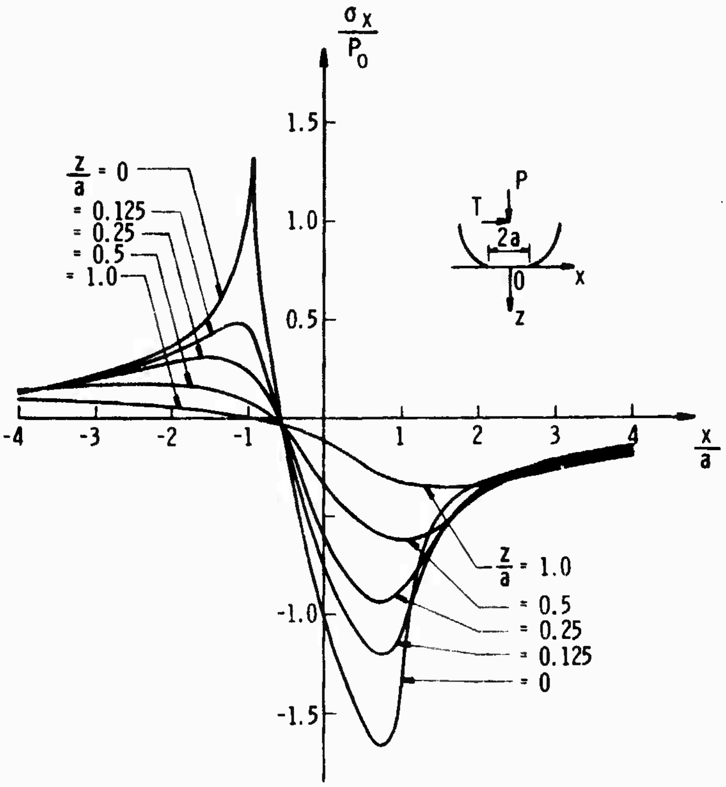


FIGURE 8 Distribution of Contact Stress For $\mu$ = 0.67. After (123).

correlate the location of cracks with the predicted locations of maximum principal stress as well as the angle of the crack plane relative to the direction of the maximum principal stress. Thus, at least for Al-4 % Cu alloy and three steels tested in air, the macroscopic stress distribution appears to predict the initiation of fretting fatigue cracking.

## C. MECHANISMS OF FATIGUE

Assume that the complex distribution of stress components (both their ranges and mean values) has been estimated. The salient aspects of fatigue crack initiation and propagation that have been identified in the absence of fretting can now be reviewed.

At temperatures below the creep range, fatigue crack initiation results from localized cyclic deformation which may:

(1) rupture protective surface films and periodically expose fresh surface to environmental attack;

(2) initiate or propagate discontinuities by irreversible cyclic plastic strain;

(3) accumulate defects such as dislocation loops and dipoles, reducing the energy required for fracture; and

(4) promote metallurgical phase transformations, precipitate resolution, particle cutting, etc., that may lower the flow stress or embrittle the material.

Plastic strain in metals occurs by dislocation motion under a critical resolved shear stress. This slip has been characterized as "planar" or "wavy," depending upon the degree to which dislocations remain in coplanar bands. The planar slip mode is typical of the early stage of fatigue crack initiation from a smooth surface in a number of face-centered cubic and hexagonal close-packed metals and alloys [Grosskreutz (76)] and is commonly referred to as Stage I cracking; the occurrence in body-centered cubic alloys is rare. Stage I cracking has been identified as a crystallographic slip plane decohesion mechanism that ranges in extent from one or two grains below the free surface in soft alloys to complete fracture in strong materials [Wells, et al. (199)]. Specifically, the extent of crystallographic cracking depends upon the mean free slip distance, the applied stress, the friction stress on the slip plane and the stacking-fault energy of the material. It can be suppressed by thermally-activated climb or cross slip at low frequencies and elevated temperatures and by high strain concentrations that enforce multiple, intersecting slip. Planar slip is associated with reversible, or "kinematic," strain hardening resulting from long-range internal stress fields of blocked slip bands, which are similar to cracks with a friction stress on their surfaces. These internal stress concentrations can be associated with stress-corrosion cracking [Douglas, et al. (44)] and with grain boundary cavitation at elevated temperature [Dyson and Henn (47)]. Stage I cracking is known to be governed both by the range of shear stress and by the normal stress across the crack plane.

Wavy slip, on the other hand, is characteristic of most body-centered cubic alloys and, in general, of high stacking-fault energy materials, high strain range and incoherent precipitate particles that cannot be penetrated by dislocations. Under cyclic loading, dense tangles of dislocations are initially produced which rearrange into cell walls of an equilibrium diameter which decreases with applied strain range and restricts the reversed motion of

dislocations [Feltner and Laird (56)].* Crack initiation and propagation in the presence of wavy slip is noncrystallographic and proceeds normal to the maximum principal tensile stress. The irreversibility of noncrystallographic plastic deformation at a crack tip results in striations on the fracture surface. The commonly observed transition from crystallographic (Stage I) to noncrystallographic (Stage II) crack propagation is associated with a plastic zone size at the crack tip of the order of the mean free slip distance (grain diameter, interparticle spacing, etc.) and is associated with a critical value of stress intensity factor (see below). The transition is attributed to a high degree of complexity of slip resulting from a large number of active slip systems.

Crack initiation and propagation can take place along grain boundaries in an aggressive environment or when a sufficient creep component of loading exists. In the former case (discussed more completely in Section E of this chapter), grain boundary segregation is required to provide an active path for selective chemical attack such as anodic dissolution, oxidation or hydrogen reaction. In the creep range, void growth by vacancy diffusion and mechanical linkup can proceed in the absence of an aggressive environment [Dyson and Henn (47)]; however, there is mounting evidence that near a free surface, the environment can greatly accelerate cavitation at grain boundaries [Scaife and James (156)] and can govern transitions between intergranular and transgranular cracking [Speidel (163)].

Crack initiation at alloy surfaces is governed by residual stress and cold work; both effects are prominent in the case of contact fatigue. Studies of the effect of shot peening, for example, have shown that in steel, nickel-base and titanium alloys, the increase in fatigue life results from residual compressive stress, rather than cold work. It has also been determined that the nucleation rate of cracks in slip bands is relatively unaffected, but that their rate of propagation is drastically reduced [Burck, et al. (31)]. In planar slip situations, the beneficial effect has been attributed to friction on the crack surface and the greater tolerance for accumulation of dislocations on active slip systems; in wavy slip situations, the benefit derives from the reduction of crack tip opening displacement under an applied tensile strain. It is pertinent to the problem of fretting fatigue to remark that the presence of subsurface defects, such as nonmetallic inclusions, is often responsible for the initiation of cracks below the layer containing the residual compressive stress; analogous situations occur in rolling contact fatigue [Barton (17)].

Fatigue crack propagation is frequently separated from initiation in order to apply fracture mechanics analysis to design. Mechanistically, the distinction is often arbitrary, but the following differences may be noted. Cracks may

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* The cell diameter is partly reversible, so that a decrease in the applied strain range, for example, results in an increase in cell diameter and concomitant cyclic strain softening. This effect does not exist in the case of planar slip.

propagate more rapidly along the free surface than into the interior if initiation is governed by a surface film or scale or by reaction with an aggressive environment. At higher strain ranges, as in low-cycle fatigue, cracks may initiate independently at numerous locations on the surface and gradually link up to form one dominant crack front.

In other respects, the practical distinction between crack initiation and propagation may hinge upon the applicability of linear elastic fracture mechanics to very small cracks, i.e., the crack propagation law for a macrocrack may not hold for a small crack in a high stress field. (It is also customary to refer to the early stages of fatigue crack growth below the limit of resolution of the particular method employed for detection as "initiation," but, fortunately, this point of view is being abandoned.) Also, the initiation of stress corrosion cracks does not appear to be amenable to fracture mechanics in some cases.

Fracture mechanics analysis of crack growth proceeds from the purely empirical observation that the rate of crack growth can be correlated with a single-valued parameter combining the loading and the geometry of the crack. In the linear elastic case, this parameter is the well-known stress (or strain) intensity, i.e., the coefficient of the inverse square root singularity in the crack tip stress field [Paris and Sih (134)]. This correlation has been successfully applied to problems of fatigue, stress corrosion cracking, corrosion-enhanced fatigue, and--much more tentatively--to creep and creep-fatigue interaction. In all cases, interest centers upon the ability of the stress intensity factor to represent the crack tip opening displacement, which is believed to govern the generation of fresh fracture surface. At applied stresses well below general yield, fracture mechanics has been shown to apply to initial defect sizes on the order of 25 microns [Dowling (45)]; when the net section stress approaches the yield stress, or is in the creep range, the plastic zone size at the crack tip no longer correlates with the stress intensity, and inelastic analyses must be employed. While mathematical solutions exist for cracks in shear, the opening mode has been analyzed only by elaborate finite-element elastic-plastic codes [Tracey (178)] or by approximate slip line field analysis [McClintock (114)]. Regions of validity of linear elastic fracture mechanics have been accordingly defined; nevertheless, the tendency has been to try the correlation and use it where it appears to work.

Extension of fracture mechanics into the inelastic loading regime is currently accomplished through a "path-independent integral" around the crack tip. The so-called "J-Integral," promulgated by Rice (144), is essentially a measure of energy applied to the opening of a crack and has undergone application to both "invalid" fracture toughness tests and creep fracture.

Fracture mechanics has been applied to fretting wear by the rupture of adhesively bonded asperity contacts [Yeh (208)] and to fretting fatigue by the propagation of cracks below the surface. While it is difficult to assess the asperity contact model, the prediction of crack propagation from surface defects is straightforward once the distribution of the stress below the surface is known.

Armed with data for the threshold stress intensity level (below which slow crack growth does not occur), it is easy to calculate the depth of a nonpropagating surface crack, or to determine whether crack arrest will, in fact, occur. This information is vital to the application of laboratory test results to the design analysis of structural components, because, in most cases, the distribution of the stress below the surface of a complex structure will not be the same as achieved in a laboratory specimen. It follows that fretting fatigue cracks that are arrested in the specimen will not necessarily be arrested in the component, and vice versa. In fact, where the possibility of fretting exists, the application of analytical fracture mechanics appears to be the only safe alternative to simulated loading of the structure.

It is interesting to note in connection with the application of fracture mechanics that "damage-tolerant design," initially developed by the Air Force for airframe structural components, is now undergoing adaptation to critical structures such as landing gear and turbine engine disks. The methodology assumes the presence of initial flaws and requires the calculation of crack propagation lifetime either to a critical size or a size reliably detectable by nondestructive examination; the lifetime must significantly exceed either the design lifetime or the time between overhaul. Extension of this procedure to fretting fatigue situations would require the specification of a conservative depth of surface crack initiation, the crack growth law for the material in the environment of concern, the decreasing-load threshold stress intensity factor and an analysis of the cyclic stress distribution.

Prediction of surface damage in the presence of fretting is the most difficult aspect of the fatigue problem and involves an understanding of the surface wear phenomenon. This subject is reviewed in the following section.

## D. MECHANISMS OF FRICTION AND WEAR

It has already been noted that fretting fatigue cracks are frequently observed to initiate adjacent to, rather than within, a wear scar. While these observations applied to the macroscopic scale, it also appears that on the microscopic scale of contact asperities, crack initiation occurs mainly at the boundary of the contact area rather than at the center. The simplest explanation is that the maximum stress occurs at the leading and trailing edges of the asperity contact. However, the distribution of stress within an array of contacts warrants detailed examination at this point.

Figure 9 indicates schematically the distribution of shear and normal stresses for a periodic array under uniform loading. Note that the component of normal stress in the surface parallel to the direction of slip, $\sigma_{zz}$, is zero at the center of the contact asperity and midway between adjacent asperities; the shear stress parallel to the surface, $\tau_0$, is assumed to be proportional to the contact pressure, $p_0$, at the interface. While the shear stress, $\mu p_0$, produces a tensile

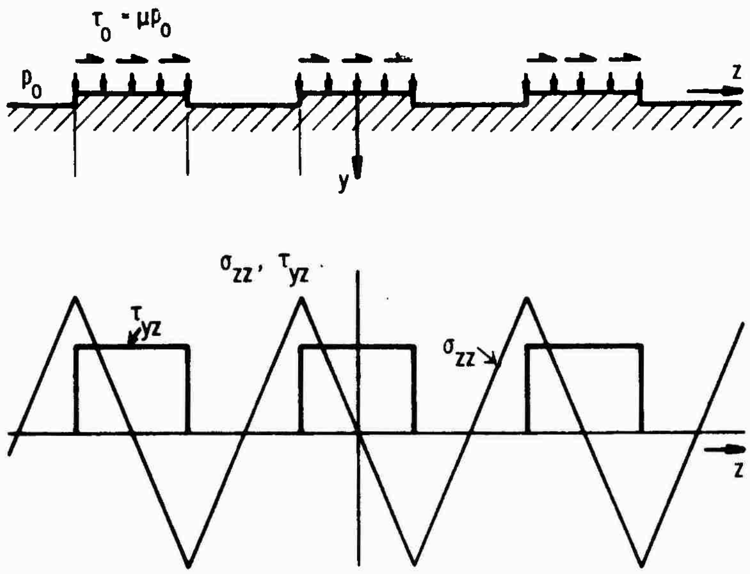


FIGURE 9 Periodic Array of Asperities Under Uniform Shear

stress at an angle to the surface, it is reduced by the compressive surface stress, for example, to a value of 0.2 $p_0$ for a coefficient of friction equal to unity. Consequently, fatigue crack initiation in the asperity contact would not be favored for materials that exhibit Stage II fatigue exclusively, although it would appear to be facilitated in Stage I. No data are available to substantiate such a correlation with crack mode.

Another factor contributing to the reduction of cracking frequency within asperity contacts may be the wear of the asperity peaks. This wear may remove crack nuclei and inhibit the usual crack initiation mechanisms at a free surface; in particular, the plastic deformation associated with the wear process may enforce complex slip at the surface, thus suppressing Stage I initiation.

Regardless of the initiation site, it is obvious that the microscopic distribution of stress around contact asperities can influence microcrack growth only over a very small depth below the free surface, on the order of the dimensions of the spacing between the asperities; it is also obvious that the concentrated normal stress, $\sigma_{zz}$ in Figure 9, is a function of the ratio of the asperity width to spacing, decreasing as the ratio increases. Thus, the maximum concentrated stress for closely-spaced contacts would be expected to occur at the boundary of the macroscopic contact area. Both the amplitude of the microscopic stress and its gradient below the surface are also governed by the rigidity of the surface asperities and the shear modulus of the material.

Certainly, there are sufficiently variable distributions of contact pressure, coefficient of friction and asperity size and spacing that no general statements

concerning the initiation sites for fretting fatigue can be made. Consequently, it is appropriate to determine what is known at present about crack formation accompanying various types of sliding.

Consider the typical adhesive wear process in which two surfaces slide over each other, usually repeatedly over the same track, and material is continually lost in the form of wear particles. At present there is more disagreement over the mechanism of adhesive wear than at any time since the process was first defined in the 1940's.

According to the classical adhesive wear model, wear occurs as a result of a process in which, during sliding, individual junctions are sometimes so strong that adhesion occurs and a junction is broken at a location other than its original interface [Rabinowicz and Tabor (141)]; Burwell and Strang (33); and Archard (12)]. Consequently, a wear particle is transferred from one sliding surface to the other and this particle eventually becomes loose and leaves the sliding system in one of several ways [Rabinowicz, 140)]. Note that this mechanism ignores cracks altogether. There may well be surface cracks, but they are regarded as being neither necessary nor sufficient for adhesive wear to occur.

In adhesive wear theories, the wear rate is affected relatively little by the microstructure of the sliding surfaces, but is influenced far more by the adhesion at the interface, as determined by the degree of cleanliness or the extent of lubrication. A good correlation between friction and wear is anticipated, and small increases of friction generally produce large increases in wear. (Naturally, not all research workers who believe in the adhesive wear theory believe all the above statements.)

Late in the 1950's, a new theory or set of theories emerged which still exists. This theory emphasizes the initiation and growth of cracks. Perhaps the first paper was by Bayer, et al. (18) which formed the basis for what came to be known as the IBM Theory of Wear. Unfortunately, this work used the macroscopic relationships for fatigue theory, but did not develop, to any extent, a model for crack growth and propagation. In the last few years, another fatigue-based theory has been introduced--the Delamination Theory of N. P. Suh (168). This theory considers the way in which dislocations, voids and cracks behave during sliding, but the main emphasis is on cracks running parallel to the surface--rather than in cracks that intersect the surface. There has also been work in this area in Israel [Rozeanu (150)] and in Japan [Endo and Fukada (49)] and Kimura (106). Unfortunately, here too the main emphasis is on cracks parallel to the sliding surfaces.

Under fretting conditions, the sequence of events is not dissimilar to that encountered in uniaxial sliding, but at present there appears to be less disagreement between various researchers (perhaps because there are fewer of them). Often the initial result of wear from adhesive effects is prominent [Waterhouse, et al. (194) and Stowers and Rabinowicz (167)]; however, in some cases a later stage is reached in which subsurface damage becomes more significant, and the

size-scale of the wear process increases. It is clear that the geometrical aspects of fretting compared to uniaxial sliding (the much higher numbers of stress reversals per unit sliding distance, and the more constant location of the regions under stress) favor fatigue mechanisms against adhesive mechanisms.

It was thought for a long time that corrosive and abrasive effects were crucial to the fretting process [Tomlinson, et al.(175)]. The role of these two effects has now been downplayed (i.e., the effects may be important but they are neither necessary nor sufficient to cause fretting damage). The corrosion-based theories were undermined by findings that materials such as gold and glass sustained fretting damage [Godfrey and Bailey (69]; the abrasion-based theories were damaged by findings that the rates of wear in fretting were lower than typical abrasive wear rates, while typical abrasive products formed during fretting (for example, metal oxides) are too small to do anything more drastic than to polish the surfaces.

One principal difference between the wear phenomena in monotonic versus oscillatory sliding is the accumulation of wear debris within the contact area. Hurricks (99) has reviewed the observations of wear product generation (primarily in air) and concluded that, characteristically, a compact of oxidized metal particles and of the metal itself separates the two surfaces; the process of amalgamation by repeated formation and rupture of adhesive contacts appears similar to mechanical alloying. This compact may be extruded at large slip amplitudes.

Perhaps the main function of the corrosion product is to lower the friction in some cases (by introducing rolling action at the interface) and to lead to stress concentrations (by removing some of the material at the interface). Both of these have a large effect on the initiation and propagation of fatigue cracks.

One of the weakest aspects of present understanding of fretting wear is that a fretted surface does not generally look like a surface that has been exposed to adhesive, abrasive or corrosive action.

In the two cases considered above, namely adhesive wear and fretting wear, adhesive wear involves effects at the interface (according to some workers), and a short distance below the surface (according to others). In the case of fretting, the primary concerns are the above effects as well as other crack formation and propagation events further below the surface. In fretting fatigue, a third stage is reached in which the crack production and growth process associated with fretting (basically surface effect) interacts with a bulk fatiguing process (a volume effect) to produce greatly accelerated damage.

This progression leads to one worthwhile generalization--namely, that since surface cracks and cracks just below the surface are less dangerous than cracks quite far from the surface, an aspect of good design against fretting fatigue would ensure that cracks be induced to remain at or near the surface. For example, treatments that confine the action to the fretting interface (e.g., the provision of a coherent soft solid lubricant film) tend to minimize fretting

fatigue, at least until the film is worn away, and, therefore, are "good." However, treatments that drive the shearing action away from the interface (for example, plating with hard materials) have the opposite effect of increasing fretting fatigue damage. The experimental data of Liu, et al. (110) are consistent with this generalization. In regard to the effect of a hard surface layer, there is a tradeoff between the reduction of friction thereby achieved and the ductility of the layer, since fracture could lead to fatigue crack growth and rapid wear. Film adherence is also important to resist debonding.

## E. EFFECTS OF ENVIRONMENT AND SURFACE CHEMISTRY

The wide range of possible environmental effects in fretting defies detailed discussion in this limited survey. This section attempts to list the known and probable effects on crack initiation and propagation in order of their significance with only cursory reference to the vast literature on wear.

From the standpoint of fatigue, it has been noted that the most important effect of surface reactions is on the coefficient of friction which itself reflects a host of micromechanical and tribological phenomena including generation, distribution and properties of corrosion product, boundary lubrication, contact asperity modification, surface alloying and cold working. The coefficient of friction governs the range of surface stress and the modification of surface defects to form potential fatigue cracks.

Next in importance are the chemical effects that may contribute to the initiation and propagation of fatigue cracks under the resulting stress distribution. These effects can be characterized as pitting, active path corrosion, stress corrosion cracking (SCC), corrosion-enhanced fatigue, hydrogen embrittlement and various high temperature gas reactions.

Corrosion in liquids requires either the presence of an active path or inelastic deformation or both. An active path is a narrow region of structural discontinuity or chemical segregation, such as a grain boundary or precipitate particle interface, which can be attacked selectively under some combination of pH and potential. The depth of attack in the absence of stress is usually very small, but can be catastrophic in some cases. The depth appears to be limited by the formation of a corrosion product that can "plug" the crevice and impede the flow of current and diffusion of electrolyte to its apex. If the attack of the material in the active path is not much faster than that of the surrounding material, a series of pits or a groove may result, rather than a crack-like defect; the condition for cracking will be met if a passivating film forms on the flanks of the crevice but is unable to form at the apex.

In the absence of an active path, inelastic deformation is required to disrupt the surface film and allow localized attack. Film rupture is aided by slip offsets, and it is believed that planar slip promotes localized attack more readily than does wavy slip, although attempts to correlate stress-corrosion

cracking susceptibility with slip character have not succeeded [Staehle (165)]. For localized corrosion to be sustained, a critical strain rate must be achieved to prevent repassivation; however, the strain rate must not be so high that general corrosion (pitting) results. The critical strain rate is found to be on the order of $10^{-6}$ $sec^{-1}$ in many systems [Scully (159)]. For SCC to occur, the rate of crack tip extension must be adequate to generate a critical strain rate or rate of crack tip opening displacement to prevent formation of a passivating film at the crack tip [Vermilyea and Diegle (183)]; this requires that the crack tip strain exceed the ductility of the growing film before the strain rate decreases to zero. If the material does not exhibit microcreep,* then no film formation can occur if SCC is to take place under static loading.

In both the active path and film rupture mechanisms of SCC, crack extension may result from anodic dissolution or by hydrogen attack; however, the precise mechanism is a subject of controversy. Hydrogen evolution, which is inseparable from anodic dissolution, may reduce the bond energy at the crack tip or diffuse for considerable distances ahead of a crack tip by grain boundary diffusion or by the "sweeping" effect of dislocations [Tien (173)]. In titanium alloys, SCC is believed to result from formation of a brittle hydride phase at the crack tip [Paton and Williams (135)].

Anodic dissolution is absent, of course, in gaseous phase corrosion. However, intergranular crack growth in the creep range exhibits many of the features of active path SCC. Most significantly, it has been observed that intergranular cracking in some creep-resistant austenitic alloys can be eliminated by replacing air by vacuum or inert environments [James (101)].

No mechanism has been advanced for this effect, but the oxidation of grain boundaries may be analogous to anodic dissolution. Gas phase SCC has been documented in hydrogen [Scully (158)], moist hydrogen sulfide, moist carbon dioxide/monoxide mixtures and water vapor below the creep range. In the creep range, where cavity formation is the dominant mechanism of fracture, the density and growth of cavities has been found to be increased by outward cation diffusion to the free surface and diffusion of adsorbed atomic gas to the cavity surfaces, whereupon gas pressurization and reduction of the surface energy of the cavities may take place [Cook and Skelton (40)]. Hydrogen may also react with carbide particles to form methane under pressure.

The superposition of cyclic loading on SCC may have no effect on the mechanism of crack growth; however, in some cases it may drastically reduce the stress required for initiation. Cyclic loading of line pipe steel to a small percentage of the yield stress has been found to reduce the threshold stress for SCC by half [Fessler (61)]. Wei and Landes (198) considered the effects of SCC and fatigue to be additive. Both the film rupture and anodic dissolution mechanisms would be expected to be accelerated by cyclic loading. In particular,

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* Primary (or exhaustion) creep is observed at room temperature with titanium and aluminum alloys, copper, mild steel and low alloy steel.

the increased strain rate from resharpening the crack tip by unloading would favor the film rupture process.

Obviously, there is insufficient information to predict the interaction between fatigue and time-dependent crack growth in aggressive environments. More than one mechanism of fracture may operate in such circumstances: fatigue crack initiation may precede stress corrosion crack growth, or vice versa, depending upon the gradients of steady and cyclic stress, access of the environment to the crack tip and the threshold stress intensity values for fatigue and SCC. In the case of fretting fatigue, it is more likely that cracks would initiate under high oscillating surface stress and would propagate in SCC if there were a sufficiently high mean tensile stress. In general, it is advisable to assume that the material will follow the sequence of mechanisms which results in the minimum fracture lifetime.

When the mean stress is low relative to the stress amplitude, or when a combination of pH and the potential which is conducive to SCC is absent, an aggressive environment may accelerate the growth of fatigue cracks. Mechanistically, there is no sharp boundary between corrosion-enhanced fatigue and SCC. The chief distinction is that the fatigue cycle, in addition to exposing fresh surface, continually reestablishes the stress distribution at the crack tip. The amount of fresh surface created in each cycle may be increased by the reduction of bond energy by hydrogen, by anodic dissolution along an active path or by film rupture accompanying microcreep; however, the growth rate of the crack, or strain rate at the crack tip, is insufficient to maintain conditions for steady-state crack growth. Consequently, the crack growth decelerates, and the crack may arrest if the frequency of cycling is adequately low or the hold time in tension is long. Crack growth per cycle is commonly found to increase with the period of the cycle both within and below the creep range. The question of saturation of the hold time effect (i.e., the arrest of cracking in a loading cycle) is of great current importance in predicting structural lifetime and is one of the least understood aspects of fracture. Researchers using the concepts of fracture mechanics are currently unable to explain the deceleration of crack growth in a uniform stress field (in which stress intensity increases with crack length).

In special cases, the rate of fatigue crack growth can be predicted from SCC data by integrating the crack growth law over the loading cycle, provided, of course, the stress intensity during part of the cycle exceeds the threshold for SCC. This behavior is characteristic of nonmetallic materials, such as glass and ceramics [Evans (54)].

Finally, the fretting process may catalyze reactions with the environment during the generation of wear debris. Also, since the amplitude of relative slip is small, the environment may be sufficiently isolated for changes in pH to occur, for example, the liquid trapped between two faying surfaces may become more acidic than the surrounding liquid. The contacts between asperities where the surface film is removed (and where the dislodged wear particles provide

sites for chemisorption and exo-electron emission) have been shown to control the reactions between a metal and a lubricant. For a comprehensive review of the considerable literature on this topic, the reader may refer to papers by Fein (55) and Rowe and Murphy (149). The effects of high pressure and temperature have also been noted; however, the sliding rates in oscillatory contact are usually much lower than in unidirectional sliding, on the order of 1 to 10 cm per second for high frequency vibratory loading, and temperature increases associated with deforming asperities would be expected to be far less important.

The accelerated rates of corrosion attributed to catalysis and exo-electron emission would appear to be significant primarily in the early stages of fretting, since the rate of fresh surface production diminishes as an intermediate layer of wear product is developed. The same conclusion would apply to other effects of surface active environments on deformation, such as the Rehbinder effect. These effects may influence the development of pits and microcracks in the early stages of adhesive wear that may propagate fatigue cracks.

## F. SUMMARY

The origin of fretting fatigue cracks is usually in surface pits. Pits are formed in the early stages of wear by rupture of adhesive contacts between asperities, which may itself be a fatigue mechanism, with microcracks propagating roughly parallel or at a slight angle to the surface. This process may be aided by oxidation or corrosion, possibly catalyzed by the wear mechanism itself. The process is inhomogeneous and strongly dependent on surface finish. The possibility of corrosion pitting occurring later in the wear process by galvanic action or formation of acid environment must be considered.

Subsurface crack initiation is possible from initial defects such as inclusions, the probability diminishing rapidly with depth below the surface.

The coefficient of friction is determined by the environment, amplitude of relative slip and the properties of the material including surface films. The coefficient of friction--along with the geometry of the contacting surfaces and the loading between them--governs the stress distribution that determines the rate of fatigue crack growth (if any) from the surface defects, and the depth at which these cracks may be arrested. The prediction of crack growth is tractable by fracture mechanics under most environmental conditions; however, identification of the local chemical composition in the contact area is usually not possible, and crack extension by active path corrosion or other forms of SCC must be considered if the material is known to be susceptible to fretting in the environment. Conservatism is called for since the ranges of pH and potential obtainable between surfaces in fretting contact are not known.

For fracture mechanics purposes, the initial surface defect depth can be assumed to be the thickness of the plastically deformed layer, which is, in turn, a function of initial hardness, contact pressure and asperity geometry.

The thickness may vary from a few to over one hundred microns and thus may exert a first order effect on lifetime or the endurance limit. While specific observations of layer depth have been reported, it is important to develop more complete prediction methods. Regardless of the mechanism of fretting, it is conservative to assume the presence of such defects in the early stages of wear. Certainly there is insufficient data to assume that microcracking occurs to a lesser depth. If cracks of a depth equal to the maximum layer thickness cannot propagate under stabilized stress distribution, the structure can be judged safe from the standpoint of fretting fatigue.

In a similar manner, the severity of subsurface defects can be evaluated by fracture mechanics from the stress distribution and geometry of the defect. If nondestructive examination to find flaws is not carried out, the probability of defects of a given size within a given distance from the surface can be determined from the examination of similar materials.

## CHAPTER 3

## DESIGN AGAINST FRETTING-INITIATED FATIGUE

### A. INTRODUCTION

Previous sections of this report have indicated that service failures of many structural components which contribute to fretting-initiated fatigue have gradually come to be recognized as a class of failures of major importance, both in terms of their frequency of occurrence and the seriousness and consequences of the failure. The earlier sections of this report have indicated that the phenomena of both fatigue and fretting are indeed complex in themselves. A serious problem exists when fatigue and fretting occur in consort and synergisms result. In this chapter, an attempt is made to illustrate, in simplified form, the various design philosophies that are utilized to avoid impairing either the operation of the structure or endangering the safety of the structure. Subsequent to this very brief discussion, a review of the concepts of design for fatigue prevention is indicated; finally the major ways that fretting-initiated fatigue is avoided or controlled in engineering practice are discussed.

### B. DESIGN PHILOSOPHY - FAIL-SAFE AND SAFE-LIFE DESIGNS

Design philosophies in existence today assume that a structure will operate safely for either a finite design life, or, alternatively, for an infinite design life. With either of this approaches, the stress or strain levels are set such that the structure can operate safely and complete the mission without danger of a premature failure occurring. Some preliminary assessment of both the strength of the material and the strength of the structure must be made prior to use of the structure in the field. Consequently, test methods have been developed to evaluate both fatigue and fretting fatigue behavior (see Chapter 4). The safe life design philosophy also is built upon the assumption that no damage will occur during the course of the structural life to impair the operation of the structure. Thus, the introduction of fretting-initiated damage becomes a challenge in the sense that the fretting damage can introduce the necessity for considering damage and its resultant effect on the safe operating life of the structure. Thus, excessive maintenance may be required to maintain integrity.

Fail-Safe Design is a process which considers the damage tolerance of the material and the structure together. In other words, inspection and

maintenance procedures are established such that if cracking occurs, it can be detected and repaired if necessary before any serious fractures of the structural component occur. Thus, consideration of damage detection capability, repair capability, and cost of inspection and repair related to structural operation and safety must be introduced in the early design stages.

With the recent introduction of fracture mechanics, crack growth concepts have become a primary consideration in evaluating and establishing the safety of any structure. When a structural component is viewed as fracture critical, it is necessary to assure through extensive testing and evaluation that the structure will perform its role satisfactorily and that no damage is introduced that was not anticipated during the evaluation and analysis. Consequently, in the fail safe structural design philosophy, it is necessary to attempt to anticipate when fretting-initiated fatigue could become a factor in impairing the safety of a structure.

Thus, in terms of coupling the effects of fretting-initiated fatigue with a design philosophy, the type of structural philosophy to be employed on a given structure must first be evaluated.

## C. ANTICIPATION OF FRETTING FATIGUE

It is necessary to know when fretting-initiated fatigue must be considered before one can introduce quantitative design concepts. Unfortunately, in most structural design challenges, fretting is encountered in the field long after the design is fairly well solidified and structural components are in production; it is then necessary to retrofit or introduce new structural components. Sometimes engineers can anticipate the possibility of fretting damage prior to its occurrence in field operation. Nevertheless, it is extremely difficult to evaluate the consequences of fretting by analysis; and usually extensive testing must be conducted to evaluate the consequences of fretting on the structure under consideration. At the same time, various considerations are often given to try to alleviate the consequences of fretting as it relates to fatigue. A fair degree of intuition and knowledge are required in the formulation of the alleviation, prevention, and control schemes. As indicated in the earlier sections of this report, an adequate scientifically founded knowledge of fretting and fretting-initiated fatigue to formulate fretting prevention systems based on a priori principles does not exist. As will be seen in two later sections of this chapter, clever application of basic principles and common sense is needed to mitigate fretting-initiated fatigue problems.

## D. DESIGN AGAINST FATIGUE

Chapter 4, Evaluation Methods (of fretting-initiated fatigue) indicates that there are several basic methods of fatigue testing. In that chapter, the reader

is directed to the American Society for Testing and Materials (ASTM) specifications or recommended practices for fatigue testing. It is worth mentioning here that a new recommended practice for both strain cycling fatigue and fatigue crack growth is emerging in ASTM. In addition, standards are emerging very rapidly for the statistical treatment of fatigue data. Terms for structural fatigue testing are being developed as well as terms that relate to spectrum fatigue loading. In addition, ASTM is directing a significant amount of attention to the proper statistical evaluation and planning of both fatigue evaluation and fretting fatigue evaluation. Basic information on fatigue design procedures is available in a number of good design handbooks [see, for example (152) or (162)]. There are numerous other references in the literature that could be consulted for evaluating design against fatigue. The following briefly discusses basic fatigue design.

The designer must select a stress level which will allow the structure to operate safely throughout its design life. In the case of fatigue, designers usually deal with either cyclically alternating loads or strains that may occur under conditions of controlled strain or controlled load in the structure. Thus, the designer must evaluate the design type that would be most applicable in the particular situation. Frequently, designers encounter unexpected fretting problems and find that the introduction of fretting damage severely restricts the operational and safety capability of a structure. When fretting is encountered in field structures, designers must introduce a quick fix to attempt to alleviate fretting. Since the necessary knowledge is not available, this is very expensive, time consuming, and risky. Thus, the designer and materials analyst frequently evaluates the fatigue behavior of basic materials by generating diagrams showing stress vs. the number of cycles to failure; these diagrams are then used to produce modified Goodman diagrams or constant-life diagrams. A newer approach utilizes diagrams that relate the alternating strain amplitude or the strain range to the number of cycles to failure and attempts to develop a sufficient body of data for evaluating a safe stress at which to operate for a given number of cycles. Often the designer is faced with the converse: that is, some stress is specified and the safe life must be determined. By proper application of safety factors, one can arrive at a "safe" design of the structure. In fatigue design, it was soon recognized that notched parts frequently have somewhat lower lives than unnotched test specimens. Consequently, a procedure was developed utilizing a fatigue life reduction factor to limit the allowable stress that could be applied to a structure to attain a given design life with some knowledge of the kind and size of notch encountered in the structure in question. Two commonly used terms in fatigue design are the fatigue notch factor, $K_f$, and the notch sensitivity index, Q. These factors were developed by conducting a sufficient number of fatigue tests on both unnotched specimens and notched specimens and developing the proper relationship.

When dealing with fatigue design, it must be emphasized that tests must be conducted on either simple test coupons or simple structural elements which, in some way, can be related to the structural components or built-up structure in question. Since fretting frequently results from contact of two mating surfaces, it also becomes necessary to conduct tests on built-up structures and to conduct more complex tests to evaluate the fatigue behavior of simple engineering materials.

To design a fail-safe structure, the designer frequently must evaluate the crack propagation characteristics of the structure under cyclic loading. In many of these problems, fretting is not a significant factor. It would be a factor in this type of design only when (1) the fretting damage can initiate flaws (cracks) in the structure after it has been designed and (2) flaws that are equivalent in size to the fretting damage or smaller were ruled out as not being important in the design of the structure to meet the fail-safe requirements. In fail-safe analysis, one may be interested in the types of flaws that could exist in field operation, and then consider the possibility that fretting-initiated damage could introduce cracks under the cyclic loads operating on the structure. These flaws could propagate to produce some catastrophic failure of the particular structural component.

In conclusion, it is to be emphasized that the designer must first generate data that are representative of the materials, structures, and structural components in question. As the designer begins to move into considerations of fretting-initiated fatigue and its effect on the performance characteristics and safety of the structure, more complex tests are needed which require additional analysis and additional considerations in the design of the testing procedure.

## E. DESIGN APPROACHES FOR MINIMIZING FRETTING-INITIATED FATIGUE

The complexities of fretting action have been discussed by many investigators who have postulated the combination of the mechanical, chemical, thermal, and other phenomena that may interact to produce fretting. Among the postulated phenomena are plastic deformation caused by surface asperities plowing through each other, welding and tearing of contacting asperities, shear and rupture of asperities, friction-generated subsurface shearing stresses, dislodging of particles and corrosion products at the surfaces, chemical reactions, debris, abrasive action, microcrack initiation, and others.

Typical sites of fretting-initiated damage include interference fits; bolted, keyed, splined, and riveted joints; points of contact between wires in wire ropes and flexible shafts; friction clamps, small amplitude of oscillation bearings of all kinds; contacting surfaces between the leaves of leaf spring; and all other places where conditions of fretting persist. Thus, the efficiency and reliability of design and operation of a wide range of mechanical systems are related to the fretting phenomena. For example, systems in which fretting is a potential failure mode would include military and civilian ground transport vehicles, armaments, surface ships, submarines, rotary and fixed-wing aircraft, turbines, compressors, missiles, nuclear power plants, precision instrumentation, control systems, prosthetic materials, and a broad spectrum of other machines and components.

While fretting-initiated fatigue is a potential failure mode in a wide variety of mechanical systems and much research effort has been devoted to the understanding of the fretting process, there is very little quantitative design data available. No generally applicable design procedure has been established for predicting failure under fretting conditions. However, significant progress has been made in establishing and understanding fretting and the design variables important

in the fretting process despite the fact that fretting phenomena is not fully understood. It has been suggested that there may be more than 50 variables that play some role in the fretting process. Of these, however, there are probably only eight of major importance. These are:

(1) the magnitude of relative motion between the fretting surfaces;

(2) the magnitude of distribution of pressure between the surfaces and the fretting interface;

(3) the state of stress, including magnitude, direction, and variation with respect to time in the region of fretting surfaces;

(4) the number of fretting cycles accumulated;

(5) the material from which each of the fretting members is fabricated, including surface condition;

(6) cyclic frequency of relative motion between the two members being fretted;

(7) temperature in the region of the two surfaces being fretted; and

(8) atmospheric environment surrounding the surfaces being fretted.

The minimization or prevention of fretting-initiated damage must be carefully considered as a separate problem in each individual design application because a palliative in one application may significantly accelerate or modify the fretting damage development in a different application. For example, in a joint designed to have no relative motion, it is sometimes possible to reduce or prevent fretting by increasing the normal pressure until all relative motion is arrested. However, if the increase in normal pressure does not completely arrest the relative motion, the result may significantly increase fretting damage, instead of preventing it.

As indicated above, one frequently evaluates the fretting-initiated fatigue performance by evaluating the reduction in fatigue life compared to the life free of superimposed fretting. After determining the magnitude of the fatigue life reduction, or the nuisance that the damage would introduce after the structure is in the field, a decision is usually then made whether the fretting-initiated fatigue must be alleviated in some manner. At this point, numerous testing procedures can be introduced to provide leads in an attempt to cause changes in the fretting development so that no damage will be produced under the structural loads encountered in field operation. Unfortunately, this procedure is frequently a trial and error process since adequate knowledge is not always available to alleviate a given fretting problem.

Nevertheless, there are several basic principles that are generally effective in minimizing or preventing fretting. These include:

(1) complete separation of the contacting surfaces;

(2) elimination of all relative motion between the contacting surfaces;

(3) if relative motion cannot be eliminated, it is sometimes effective to superimpose a large unidirectional relative motion that allows effective lubrication; for example, the practice of driving the inner or outer race of an oscillatory pivot bearing is effective in eliminating fretting;

(4) provision for compressive residual stresses at the fretting surface; this may be accomplished by shot peening, cold rolling, or interference fit techniques;

(5) judicious selection of material pairs;

(6) use of interposed low shear modulus shim materials, such as lead, rubber, or silver;

(7) use of surface treatments or coatings as solid lubricants; and

(8) use of surface grooving or roughening to provide debris escape routes and differential strain matching through elastic action.

Of all these techniques, only the first two are completely effective in preventing fretting. The remaining concepts, however, may often be used to minimize fretting damage and yield an acceptable design. The utilization of surface films and lubrications is of such significance in design to alleviate fretting that some further discussion is warranted.

## F. SURFACE FILMS AND LUBRICATION METHODOLOGY TO ALLEVIATE FRETTING-INITIATED FATIGUE

The placement of low shear strength material at the interface of two contacting surfaces is an approach to mitigating fretting-initiated fatigue. These films reduce the coefficient of friction to allow smoother relative movement and/or reduce the availability of oxygen, moisture and other environmental pollutants which may abet fretting wear and fretting processes. A second method is to modify the "surfacial layers" of the contacting surfaces so as to both increase hardness and induce compressive stresses. The degree of success is varied depending upon the metallurgy, composition, and method of film application and the working environment of the system.

Surface films can be applied in the form of liquid lubricants, greases or solid coatings. The method of application is governed in many cases by the accessibility and the ease of replenishing the film. Solid coatings must be used where the components are totally inaccessible.

## G. LIQUID LUBRICANTS

Liquid lubricants can be used only where it is feasible to supply fluid on a continuous or semi-continuous basis, and then success has been marginal. In (1) and (187) discussed in the Appendix, evidence is given to show that mineral oils reduce fretting wear. The mechanism is believed to be one of lowering the coefficient of friction and lowering the diffusion of oxygen to the surface. Boundary additives that reduce the coefficient of friction also may help on the friction and wear side, but could be harmful in regard to crack propagation, so that their overall effectiveness may be small. Extreme pressure additives can help by reducing fretting wear and inhibiting crack initiation but their influence on crack propagation is not known.

As a general statement, liquid lubricants are not the answer since, in most systems, it is impossible to maintain a supply of lubricant at the contact interface.

## H. GREASES AND PASTES

Greases are superior to liquid lubricants in their ability to remain in the contact interface because of the structure of the grease and its rheological properties. The grease acts more or less as a reservoir for oil to migrate into local areas of the asperity-asperity contact to combat fretting wear and the initiation of fatigue cracks.

A variety of additives can be incorporated into a grease, including any of the friction wear mitigating additives that are added to oils, plus solid molybdenum disulfide, graphite, and polytetrafluoroethylene (Teflon) powder. These latter additives have been shown to exhibit some response in some applications [Overd (132)] and $MoS_2$ in a lithium stearate grease was effective in reducing fretting fatigue of L-65 aluminum alloy pin joints.

In general, greases offer some benefit but their life appears limited due to the buildup of fine wear debris in the grease which modifies its properties and effectiveness. Therefore, the use of greases and pastes in many applications has not been considered a permanent solution, but rather a temporary fix. This would be especially true in inaccessible areas of complex systems.

However, additives with superior anti-fatigue properties are being developed so that, in the future, the potential should exist to formulate greases with superior fretting-fatigue properties to those made today. In one case, the development

of an oil which has superior anti-fatigue properties in the presence of moisture contamination has been reported (Armstrong, et al., 14). An approach to reduce fretting fatigue by additive chemistry does not appear to have received much attention in the past. This is an approach that deserves investigation and is one that could be productive for applications where the use of grease and/or lubrication is feasible.

## I. COATINGS AS SOLID LUBRICANTS

Any solid film that will stay in a contact zone and maintain its integrity with time is a potential solid lubricant for mitigating fretting fatigue. Many materials have been tried, including $MoS_2$, zinc oxide, Teflon, and soft metals. In many cases, the solid lubricant is bonded to the surface with a resinous material. The level of improvement appears to be dependent on the substrate metallurgy, stress level, and environment. At this time, there does not appear to be any clear guidance as to the selection of materials, since a given material may totally alleviate the problem in one application, and have little or no success in another. Also, sometimes a given lubricant that works in one situation will produce a disastrous result in another one which involves some difference in the fretting or fretting-fatigue situation.

By comparison to oils and greases, dry coatings containing solid lubricants of low shear strength are clearly superior. However, most coatings do exhibit a fair amount of wear so that they also have a limited life.

## J. SURFACE TREATMENT

A coating can be formed by chemical reaction of the outer atomic layers of the metal. Such coating processes are carburizing, nitriding, phosphatizing, and sulphurizing. These processes lead to surfacial layers which possess markedly different wear properties of the metal substrate and can improve the fatigue strength. Little detailed information is available on their success in fretting fatigue; consequently, this is an area that needs extensive investigation.

## K. ION IMPLANTATION

Recent research (9) and Hartley, et al. (84) have shown that the implantation of ions into the surfaces of metals greatly improves their resistance to wear and leads to a lower coefficient of friction. Almost any element is capable of being implanted. The incorporation of ions in the lattice of a metal changes its strength and its adhesion properties in sliding contacts.

Although this technique is being used in the semi-conductor industry, its potential application in the engineering materials field is relatively new. It would appear that ion implantation needs to be investigated as a potential solution to some fretting fatigue problems, especially those which are difficult to solve by more common methods.

## L. SUMMARY

It is necessary to evaluate the seriousness of fretting-initiated fatigue in any specific design by conducting simulated service tests on specimens and/or prototype components. Within the current state-of-the-art knowledge of fretting fatigue, there is no other safe course of action open to the designer.

One must clearly anticipate if fretting might be a problem, and it is frequently best to anticipate this by conducting tests simulating service. When fretting is not anticipated properly and the problem is encountered in the field, one is faced with developing the means of alleviating the fretting fatigue situation. This is extremely difficult. The alternatives are either to shorten the design life, or reduce the load.

# CHAPTER 4

# EVALUATION METHODS

## A. INTRODUCTION

The purpose of this chapter is a brief review of evaluation methods pertaining to fretting, fatigue, and fretting-initiated fatigue. While standard test methods or recommended practices in fatigue testing appear to be developing at a reasonable pace, the same cannot be said for either fretting or fretting-initiated fatigue. The question of standardized test methods for the latter two appears to be similar to the situation in thermal cycling, where no two organizations (or individuals for that matter) appear able to agree on so much as a standardized test specimen. Given the uncertainties as to the effect of critical variables existing in fretting problems, it would seem that the safest evaluation methods would involve simulated service testing or careful case studies of actual service failures (1). However, economic constraints, time and safety factors require that acceptable, accurate, inexpensive, and relatively short-term laboratory evaluation techniques be developed for future use.

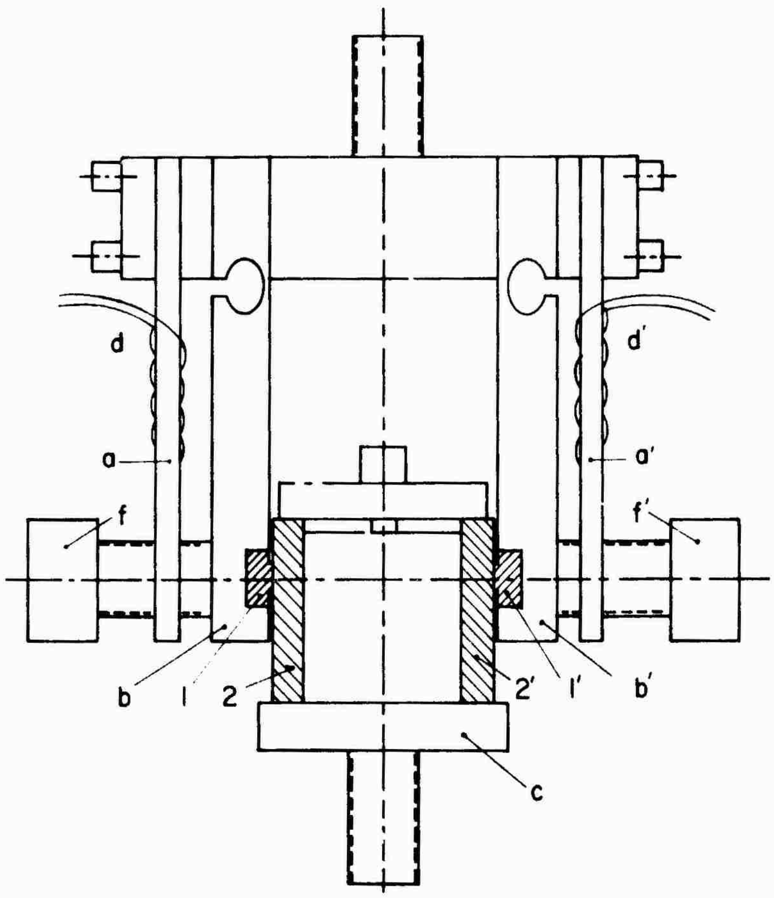
## B. FRETTING (WEAR-CORROSION)

Waterhouse (187) has summarized a number of experimental studies of fretting wear and corrosion and documented the wide variation in equipment that has been used.

Examples of equipment and evaluation techniques used in recent studies are given by Toth (176) and by Stowers and Rabinowicz (167). Schematic drawings of the apparatus and specimens used by Toth follow in Figures 10 and 11 respectively.

A schematic diagram of the fretting apparatus utilized by Stowers and Rabinowicz is shown in Figure 12. This apparatus was capable of operation at relatively high frequencies.

In addition to the presentation of these figures, some details and evaluation techniques gleaned from the literature are described in the following sections.




| | | | |
|---|---|---|---|
| 1-1' | Immovable specimens | c | Specimen holder |
| 2-2' | Movable specimens | d-d' | Strain gages |
| a-a' | Spring arms | f-f' | Screws for adjusting desirable load |
| b-b' | Specimen holders | | |

FIGURE 10 Schematic Drawing of the Experimental Setup

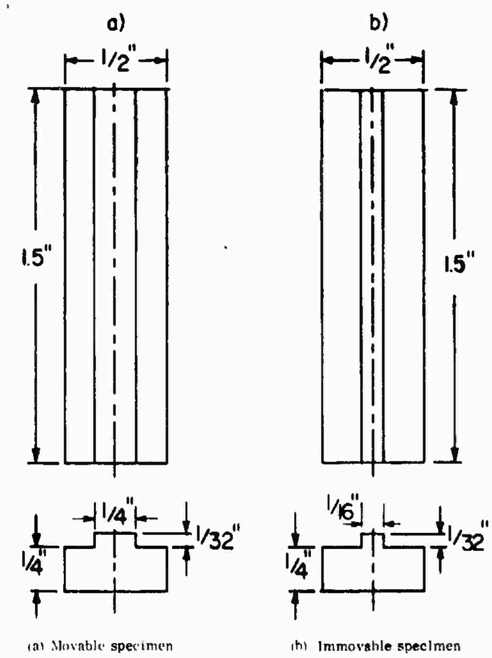



FIGURE 11 Fretting Specimen Dimensions

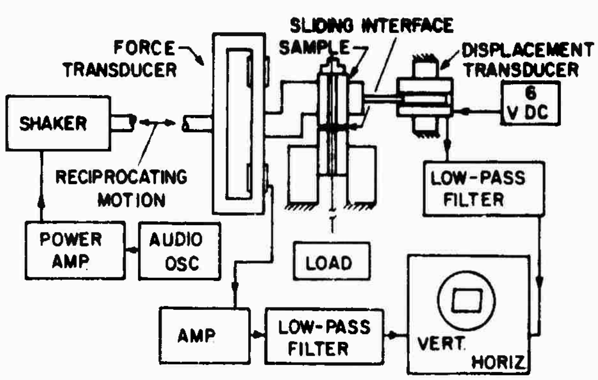



FIGURE 12 Schematic Diagram of High-Speed Fretting Apparatus

## C. FRETTING WEAR AND FRETTING CORROSION EVALUATION METHODS

Fretting wear experiments typically involve the vibration of one material surface relative to a mating material surface followed by a post-test evaluation of the distress to the surfaces. Some of the inevitable experimental difficulties include the relatively small amount of material affected by the fretting experiment, interaction of rig dynamics with intended motion making detailed control and measurement of interfacial forces and motions difficult, and the sensitivity of fretting wear to the test environment.

Some of the evaluation methods that have been reported inc[illegible]

(1) fretting wear volume measurements;

(2) friction force measurements;

(3) interfacial adhesion force measurements;

(4) microscopic study of the fretted regions;

(5) fretting debris weight measurements;

(6) fretting specimen weight changes;

(7) interfacial electrical conductivity measurements;

(8) x-ray analysis of debris;

(9) electrochemical current measurements; and

(10) displacement measurements (for example, spline tooth wear).

Usually two or more methods are used in conjunction with one another to provide a combination of quantitative data (for example, wear volume or friction force) with qualitative observations (for example, microscopic studies and x-ray analysis). These combinations are employed to give an indication of the extent of fretting damage and the physical and mechanical processes promoting fretting.

Some of the earliest fretting corrosion studies were reported by Tomlinson, et al. (175). The primary experimental results were in the form of microscopic fretting region examination in which debris quantities and surface conditions were used to compare the extent of fretting damage for different material combinations and lubrication conditions. These observations were supplemented with frictional force measurements. Probably the most important conclusion from their work was the concept that some interfacial slip, perhaps no more than a few lattice parameters in magnitude, is a prerequisite for fretting corrosion. The authors were able to draw that conclusion because of their ability to accurately gauge interfacial slip distances, using a cleverly designed optical lever, and to correlate the slip distances with frictional torque trends. The post-test qualitative assessments available to them were not really sufficient to enable a very specific study of the fretting mechanisms.

Dynamic microscopic observations of the fretting process, reported by Godfrey (68) and by Godfrey and Bisson (70) showed an initial strong adhesion stage followed by surface disintegration mechanisms with the generation of debris at the fretting interface. The experimental method involved vibrating a selected material (spherical surface) against a transparent flat surface, and observing the process microscopically. The generation of surface cracks by adhesive traction forces was directly observed. By fretting nonoxidizing material pairs, the authors were able to conclude that the fretting process can take place independently of the corrosive mechanism. The effectiveness of various anti-fretting surface coatings was assessed by observing the first appearance of metal surface distress, or red oxide debris generation. Thus, by using dynamic microscopic observations alone, conclusions could be drawn as to some of the mechanisms involved in the fretting process. Qualitative as this technique is, quantitative comparisons are very difficult, and some of the observations require considerable interpretation.

Feng and Rightmire (57) and Feng and Uhlig (58) relied almost entirely on specimen weight loss measurements in their fundamental study of the fretting of mild steel. To obtain measurable weight losses, the authors employed a continuous contact geometry (annular), very high unit loads (27,000 psi) and a comparatively large slip amplitude (0.003 in.). The necessity to correct for elastic rig displacement was acknowledged. By observing how the measured weight losses varied with slip amplitude, frequency, load, temperature, test environment and test duration, they proposed a two-component fretting corrosion model consisting of a frequency sensitive corrosion component, and a frequency insensitive mechanical damage component. It has proved generally difficult to reproduce Feng and Uhlig's frequency trends and it is tempting to speculate that certain rig dynamic problems may have contributed to the results. The heavy interfacial loads and large fretted area no doubt made the weight loss technique feasible, but cleaning and handling procedures invariably introduce some uncertainty into weight loss measurements.

Halliday, and Halliday and Hirst (77 and 78) used a combination of wear volume measuremements, frictional measurements, contact resistance measurements and microscopy in their study of the fretting corrosion of mild steel. A V-block cylinder specimen arrangement was employed, effectively localizing the fretting effects because of the concentrated nature of the contact geometry, thereby enabling accurate wear measurements to be made and aiding in microscopic examination. The frictional and electrical resistance measurements supplemented one another, enabling the clear identification of an early adhesive fretting wear stage, followed by debris-related mechanisms. By combining the complementing wear measurements and microscopy studies, a concise description of the sequential fretting wear mechanism and the effect of various fretting parameters was made possible. The sequential concept, supported by the combination of several evaluation methods, is still generally accepted.

A conforming specimen geometry (annular design) was used by Wright (203 and 205) with wear volume measurements giving the extent of fretting damage. The method of measuring the wear volume, also employed by Halliday, was one of successive lapping and measurement of visible fretting areas. Thus, the area distribution of damage depth was obtained. Wright was able to correlate his wear volume measurements with various mechanical and microstructural properties of the steels and cast irons he investigated. Used alone, this evaluation method did not give insight into the mechanisms of fretting.

Bethune and Waterhouse studied fretting by measuring the electrical corrosion current (21) and the coefficient of adhesion of various metal pairs (20). Both of these studies indicated the significance of oxide film disruption in promoting fretting wear. In addition, the role of intrinsic metal hardness in fretting wear was deduced, and the effect of slip amplitude on interfacial adhesion was observed. Real insight into the fretting process and actual susceptibility of various materials to fretting damage could not be learned from the adhesion and electrochemical current evaluation measurements alone.

Over the past ten years, the availability of the scanning electron microscope (SEM) has increased the amount of post-test information obtainable from fretting wear experiments and has permitted more detailed studies of fretting mechanisms and types of associated surface damage. The fretting mechanism sequences first identified in the work of Godfrey (68) and Halliday (77 and 78) were augmented by the observation of features directly indicative of surface fatigue mechanisms [Bethune and Waterhouse (20 and 21) and Hurricks (97)]. Also, the protective nature of surface oxide films and their mechanisms of disruption under high temperature fretting conditions have been investigated with the aid of scanning electron microscopy [Bill (25) and Hurricks (98)]. Invariably, the use of the SEM has been in conjunction with at least one other quantitative evaluation method such as wear volume measurement or friction measurement.

Assessment of the extent of fretting wear damage in mechanical components such as bearing housing surfaces, splines, and gear flanges is usually based on visual inspection of the fretting surfaces, observation of amount and type of debris present, and sometimes normal displacement measurements. The latter evaluation technique is often used in spline wear measurement. A spherical tipped probe is firmly inserted between adjacent spline teeth, and the normal movement required for seating gives an indication of the amount of material removed. Usually the amount of fretting wear involved in experimental fretting work, and in mechanical components other than splines, is too small for assessment by means of normal displacement measurements.

The accuracy and significance of any of the evaluation methods discussed are affected by the geometry of the fretting experiments and the degree of control exercised over the fretting conditions and parameters. The experimental geometries employed fall into two broad categories:

- constant area conforming geometries; and
- concentrated contact geometries.

The conforming geometry experiments have the advantages of maintaining constant nominal interfacial loads, and bear close similarity to many applications involving fretting. The disadvantages of the conforming geometries are that specimen alignments are critical, accurate quantitative measurements (wear volumes) are difficult, and microscopic observation is difficult because the fretting damage is not localized.

Among the advantages of the concentrated contact are the elimination of some specimen alignment problems, localization of the fretting damage enabling easy wear volume measurements and microscopic observation, and a similarity to concentrated contact bearing applications. Probably the most serious disadvantage of concentrated contact geometry experiments is the relative ease with which debris can escape the contact zone. The ratio of fretting wear scar size to slip amplitude is probably the cause of this drawback. A further apparent disadvantage of the concentrated contact experiments is that the nominal contact stress varies as wear progresses. This effect has its greatest importance in the early stages of fretting during which the wear area changes most rapidly; beyond this point, the true contact area is no longer limited by the apparent area in contact--"run in" has occurred.

It should also be kept in mind that even conforming surface geometries undergo an initial run-in period during which interfacial stresses reach a steady state value. The importance of the experimental geometry employed as it might affect generality of the fretting wear results should be better understood. It is suggested that either the literature be culled for pertinent data showing the degree of comparability between results obtained using various geometries, or an experimental program be set up to investigate this question.

In most of the recent fretting work, the investigators have done a good job of reporting relative humidity levels, and most actually control the humidity. A thorough investigation of fretting should include humidity effects because, over certain ranges, humidity strongly influences fretting results. A suggested approach to including humidity considerations is to conduct experiments in dry air, air of intermediate humidity (say 30 percent to 60 percent), and in moisture-saturated air. The influence of humidity, and relative severity of fretting in various humidity environments is seen to vary from one material to another.

Considerable literature is published on the evaluation of fretting-resistant coatings for various materials, generally employing coated and uncoated surface wear rate measurements as the primary criterion for comparison. Qualitative observations (similar to those done for fundamental fretting wear studies) relating to the mode of coating wear, for example, spallation, plastic displacement and cracking should also be made. The qualitative observations can be as significant as the wear observations in terms of the way the coating and coated components may perform in service.

Except for a few isolated pieces of work, studies of the effectiveness of various liquid and grease lubricants as fretting inhibitors are conspicuously lacking in the literature. Part of the reluctance of investigators to enter these areas probably stems from difficulties in fully characterizing lubricants and because the way in which the lubricants are introduced or applied to the fretting surfaces influences the results. Some standardization is in order here.

Some new surface analysis tools are available, and can enable a detailed assessment of the structure and composition of fretting surfaces. Elemental surface compositions can be determined by means of Auger electron spectroscopy which, in conjunction with sputter-etching, can reveal compositional variations with depth. Electron spectroscopy for chemical analysis (ESCA) can provide further information on the oxidation state of the elements on the surface. Localized variations in surface and subsurface composition of fretted regions have been studied in the SEM by employing energy dispersive analysis of x-rays (EDAX) auxiliary equipment. The techniques mentioned are but a few of the new capabilities available that can enable a more thorough evaluation of the effects of fretting on material surfaces.

Areas for possible expansion of study are:

(1) specialist studies of fretting, for example, on splines, bearings, slideways, helicopter components (a number of reports are available, principally directed toward specific solutions, i.e., lubrication techniques and coatings);

(2) evaluation of coatings (considerable literature has been published on the evaluation of various coatings as fretting wear/corrosion inhibitors); and

(3) evaluation aspects relating fretting wear to fatigue crack initiation. (no explicit studies seem to have been published--many implicit results have been published as part of fretting fatigue programs; critique may be in order here).

## D. FATIGUE EVALUATION

While it is a relatively recent development for "standards" to be published for fatigue testing, books giving recommended practice in testing and analysis of results have existed for many years. Examples of such publications are (3, 79, 113 and 162). More recently, some testing standards have been prepared and may be found in the Annual Book of ASTM Standards, Part 10 (11). The 1975 edition indicates that these are tentative; however, since publication of that edition, the membership has approved the recommended practice as standard. Specifically these designations are:

E206: Definitions of Terms Relating to Fatigue Testing and Statistical Analysis of Data

E466: Constant Amplitude Axial Fatigue Tests of Metallic Materials

E467: Recommended Practice for Verification of Constant Amplitude Dynamic Loads in an Axial Load Fatigue Testing Machine

E468: Recommended Practice for the Presentation of Constant Amplitude Fatigue Test Results for Metallic Materials

The standardization of fatigue data for <u>axial</u> loading conditions not only avoids confusion as to the state of stress existing during the test, but also permits expression of the fatigue behavior of a given material in terms of simple fatigue "properties" which can be tabulated in data books, or the data can be utilized in computer input for fatigue life prediction under spectrum loading. A "cyclic" stress-strain curve comparable to the monotonic true-stress-strain curve [Manson's Universal Slopes Rule (112)] for low cycle fatigue can be simply expressed in a power function as:

$$\sigma_a = K' \left(\frac{\Delta\epsilon_p}{2}\right)^{n'}$$

where $\sigma_a$ is the stable stress amplitude,

$\frac{\Delta\epsilon_p}{2}$ is the plastic strain amplitude,

$K'$ is the cyclic strength coefficient, and

$n'$ is the cyclic strain hardening exponent.

The total strain versus life curve can also be simply described in terms of four fatigue "properties" of the material, for example:

$$\frac{\epsilon_T}{2} = \frac{\sigma_f}{E} (2N_f)^b + \epsilon'_f (2N_f)^c$$

where the four "properties" are:

(1) $\sigma'_f$ = the fatigue strength coefficient

(2) $b$ = the fatigue strength exponent

(3) $\epsilon'_f$ = the fatigue ductility coefficient

(4) c = the fatigue ductility exponent

and the other terms are simply the total strain amplitude, $\epsilon_T/2$; E, the elastic modulus, and the number of reversals to failure, $2N_f$ (two reversals = one cycle). Utilizing log-log scales, Figure 13 is a simple representation of the total strain versus life curve, where the elastic strain components and plastic strain components are added to give the total strain.

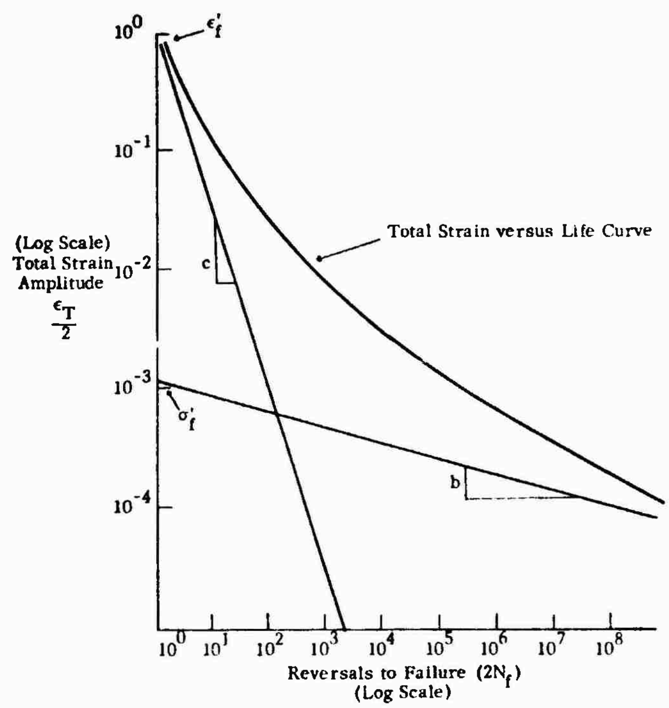



FIGURE 13 Fatigue Life as a Function of Total Strain in Axial Loadings

While the present ASTM standards for fatigue testing are based on the axial load or axial strain fatigue cycle, most laboratories have a wide variety of machines which subject a specimen to different types of loading, some of which may correspond more closely to the service condition than the repeated axial load. Some typical machines are the repeated torsion machine, the rotating cantilever beam machine, the "R. R. Moore" or four-point loaded rotating beam machine (which applies a constant bending moment to the test section of the specimen) and different variations of the paddle bar or plate specimen (the plane bending type of machine which can be adjusted to apply a

completely reversed stress or strain cycle about some nonzero mean stress). The specimen in the latter type of machine usually has a combination of constant thickness and tapered test section and is usually loaded through the point of intersection of the tapered sides. In the elastic range, this latter test method leads to a constant fatigue stress cycle throughout the test section of the specimen. In attempting to evaluate fatigue strength of a material at some reasonably large number of cycles to failure (such as $2 \times 10^6$ cycles, for example), these various test methods and machines yield reasonably reproducible results. However, if the yield strength of the material is exceeded at some part of the load cycle, the resulting strains are a mixture of elastic-plastic response and the results become rather difficult to interpret and some reproducibility of results is also lost.

## E. EVALUATION OF FRETTING-INITIATED FATIGUE

Studies of fretting-initiated fatigue are conducted on three levels of experimental complexity. On the simplest level (if anything concerning fretting fatigue can be described as simple) are the fundamental studies in which the basic mechanisms of fretting fatigue are investigated. Fundamental studies typically involve fatigue specimens with simple stress distributions, easily reproducible fretting contact geometries, and straightforward load cycle patterns.

Application-oriented fretting fatigue research is generally directed towards specific problems encountered in mechanical components. Examples of such investigations include the work of Rodriguez and Lawton (147) on helicopter rotor hub fretting problems, and Sandifer (154) on fretting of riveted cap joints. Specimen configurations invariably incorporate geometric stress raisers comparable to those of the prototype application (for example, bolt holes, bushing-clevis interfaces), and sometimes the specimens actually amount to a reduced scale model of the mechanical component. Efforts are usually made to subject the specimens to realistic loading spectra. Solutions must be found to particular fretting problems such as effective coatings or surface treatments, and and data on estimates of component service life must be gathered. Uncoated, untreated interface, or some state-of-the-art approach to fretting fatigue usually serves as the baseline in these studies.

Finally, full-scale testing of components is undertaken in those cases in which fretting fatigue is identified as the cause of failures in service, in order to demonstrate acceptable component life, allowable stress levels in the component, or the suitability of recommended fixes. Very often, accelerated testing is applied to these full-scale components, with higher than design loads imposed. From such accelerated testing, acceptability of the component life and design conditions are deduced. There are serious questions about the validity of extrapolated data on expected component service life from accelerated testing which involves higher than design fatigue stresses.

The remainder of this chapter contains a critique of evaluation methods employed in fundamental studies of fretting-initiated fatigue. Models with general applicability were sought. Since applied research, on the other hand, is most often directed toward solutions to particular problems, experimental techniques and geometry are usually guided by the application in mind. In these cases, fretting-fatigue life measurements alone are usually sufficient as evaluation means.

The primary evaluation criterion used in fundamental fretting fatigue studies, however, is a measure of the extent to which fatigue life is degraded by the effects of fretting. The baseline is almost always the unfretted fatigue life of the materials under investigation as measured by the investigator using his own specimen configuration and test apparatus. Fretting effects are introduced by application of fretting pads to the fatigue specimen; many fretting pad support and loading schemes are reported in the literature. Results are usually presented graphically in the form of an S-N type curve with both fretting-fatigue data and baseline data being plotted. Significant variables in experimental technique include:

(1) sequence in which fretting and fatigue are imposed;

(2) specimen geometry (both of fatigue specimen and fretting pads);

(3) fretting displacements;

(4) fatigue stress levels;

(5) fretting contact loads;

(6) test environment;

(7) material combinations; and

(8) cyclic frequency.

Beside measurement of fatigue life reduction due to fretting, fundamental studies often include fretting frictional force measurements, and microscopic examination of the fretting damage. However, few investigators have included crack growth studies in their experimental evaluations [Endo and Gotto (50)].

Collins and Tovey (39) performed a series of experiments on 4340 steel, following a procedure in which the fatigue specimens were first subjected to 100,000 fretting cycles of 0.003 inch displacement under a 10,000 psi contact load, without simultaneous fatigue. Flat-faced conforming fretting pads, also utilizing 4340 steel, were used for the fretting exposure. After being subjected to fretting, the specimens were then fatigued. By separating the fretting and fatigue exposures, effects due to direction of fretting relative to the axial fatigue loading direction could be deduced, and the significance of static stresses imposed on the fatigue specimen while being subjected to fretting were identified.

A drawback of this procedure, however, is that the interactive effects of fretting and fatigue are not assessed.

Most researchers follow a procedure whereby fretting and fatigue are simultaneously imposed, usually taking advantage of strain motion due to the applied fatigue stress to promote fretting. Examples of this procedure are found in (93, 111, 121, 122, and 146).

Hoeppner and Goss (93) used an axial fatigue setup with fretting provided simultaneously with fatigue by means of flat conforming pads loaded against the flat surface of the fatigue specimen test section. Elastic strain of the fatigue specimen during stress cycling provided the fretting motion relative to the rigidly-supported stationary pad. Using this experimental arrangement, the authors were able to conclude that normal load effects are significant with the Ti-6Al-4V alloy and not with 7075 Al [Goss and Hoeppner (75)]. A procedural variation in which the fretting pads were removed prior to failure of the fatigue specimen led to the concept of a fretting-fatigue damage threshold [Hoeppner and Goss (89)]. In essence, a number of fretting cycles are required to start a critical crack and early fretting fatigue failure; exposure to further fretting cycles does not further accelerate fretting fatigue failure. Frictional force measurements and slip displacement were not reported in these investigations.

Malkin, Majors and Courtney (111) also followed a simultaneous fretting and fatigue exposure procedure utilizing an axial fatigue specimen arrangement. Rather than a conforming contact geometry, cylindrical fretting pads were used (Ti-6Al-4V pads and fatigue specimens). Again, a strong fretting fatigue life dependence on normal fretting load was found. Close attention was paid to frictional sources, slip measurements, and electrical contact resistance between the pads and the fatigue specimen. These measurements enabled a determination of relative adhesive forces during fretting fatigue, and also of relative debris generation. It was proposed that when a large amount of slip could occur, debris generation led to reduced contact stresses, and wear damage led to "erasure" of initiating cracks with consequently less effect due to fretting on fatigue life.

A cantilever fatigue specimen arrangement was used by Nishioka and Hirakawa (122) with fretting introduced simultaneously with fatigue by means of cylindrical fretting pads loaded against the maximum bending stress section of the fatigue specimen. High carbon steel fretting shoes were used in conjunction with various alloy steel fatigue specimens. Relative slip and coefficient of friction measurements were made. Pits and nonpropagating cracks were observed in the fretted region, but most of the fatigue life reduction under fretting fatigue conditions was attributed to local frictional stress concentrations in the contact area. An analytical development of stress levels under fretting fatigue conditions, in the contact area, is presented.

The effect of contact geometry on fretting fatigue life was studied experimentally and analytically by Roberts (146). Simultaneous fretting and fatigue were applied to SAE 1045 steel, in contact with 1045 steel pads using an axial

stress fatigue load arrangement. For a given average contact pressure, greater reductions in fatigue strength were seen with cyclindrical fretting pads than with conforming (flat) pads. However, above a certain level of contact stress, fatigue life was not affected. The experimental results also indicate the importance of contact stress distributions on the very local asperity level.

Waterhouse and Taylor (197) employed a rotating beam bending fatigue arrangement with a "bridge" design fretting pad configuration in fretting fatigue studies on 0.7 percent carbon steel. The span of the fretting pad bridge combined with bending motion of the fatigue specimen promoted the fretting action. The clamping pressure between the bridge and fatigue specimen was about 800 psi. Through microscopic investigations, the boundary between the slip and nonslip regions was identified as being the location of fretting-initiated fatigue cracks.

In his book, Fretting Corrosion, Waterhouse rather thoroughly summarized the fretting fatigue work published up to 1968. From his summary, and the brief overview of more recent work presented in this report, it is possible to suggest some guidelines for fundamental fretting-fatigue investigations.

(1) The fretting sequence predominantly followed at present is that of simultaneous fretting and fatigue. It is probable that Collins and Tovey (39) have essentially exhausted what can be learned from sequential fretting and fatigue investigations--the effects of pit-digging, abrasive striation generation, and static crack initiation effects during the fretting exposure. The bulk of future work should follow the simultaneous fretting fatigue exposure test pattern.

(2) Axial, flexural, and rotating bending fatigue loading schemes have all been used and at least qualitative consistency is seen in the results obtained where comparisons are possible. Future investigations, which hopefully will include some studies of crack propagation phenomena, will be more straightforward if a constant stress cross-section axial geometry is employed. Results from other fatigue specimen geometries, more simply tested, also will continue to be meaningful. Effects of fretting pad geometry (conformal, line, or point contact) are still not clearly understood; in any case, the influence of contact effects on the asperity level seems to play a significant role. More future effort should be directed toward further clarifying the effects of contact geometry on all levels. A good start is provided by the works of Yeh and Sinclair (209), Roberts (146), and Nishioka and Hirakawa (122).

(3) Extensive evaluation of fretting displacement effects are presented in Fretting Corrosion (187). Briefly stated, maximum fretting-fatigue degradation seems to occur in the $8\mu$ to $15\mu$ ($15 \times 10^{-6}$m) slip amplitude range. This is consistent with the observation that some

slip must occur for fatigue strength reduction, but if slip occurs over the entire contact interface, fatigue life will be relatively less affected. Hence, fundamental fretting fatigue investigations should be conducted such that nominal slip amplitude is 15μm or less, and that the entire fretting interface does not see uniform slip (that is, over some fraction of the contact area, no slip should occur). There are many fretting pad support-fatigue specimen arrangements that will inherently provide this contact condition. Ideally, control of the slip amplitude should be independent of fatigue stress levels.

(4) In most fretting fatigue experiments, primary attention is directed toward fatigue stress levels corresponding to the high cycle ($10^6$ to $10^7$) portion of the unfretted S-N curve. This is appropriate as the effects of fretting essentially amount to an acceleration of crack initiation and the unfretted high-cycle fatigue life is dominated by the number of cycles required to "initiate" a crack.

(5) Fretting contact stress levels are seen to have an important effect on fretting fatigue of some materials and a secondary effect on others. It should probably be considered as a variable for investigation in future fundamental fretting fatigue studies.

(6) Little effort has been extended to control the test environment in fretting fatigue studies. Most work is conducted in room air at room temperatures, and usually even the relative humidity range is not reported. In view of the effects of humidity, temperature, and other aspects of the experimental environment on fretting wear as well as on the corrosive mechanisms of crack propagation, a better job of reporting and control in this area is imperative. Environmental effects should be addressed as controlled experimental variables in future work.

(7) Material combinations have been, and are, guided by practical considerations of their use in mechanical components (for example, extensive employment of aerospace structural alloys in fretting fatigue studies). Usually, the heat treatment and mechanical condition of these materials is well documented. However, some fundamental research should be undertaken involving the effects of various textures, grain sizes and structure, extent of cold work, and crystallographic orientation (currently being studied by Prof. Hoeppner). These studies might best be undertaken on simple metallic systems, perhaps elemental metals. It might also be pointed out that inadequate work has been conducted on fretting

fatigue of nonmetallic systems. Increased use of nonmetallics (ceramics, plastics, composites, etc.) in the future makes this more than an academic concern.

(8) Cyclic frequency seems to be of secondary importance in fretting fatigue, judging from the summary in (187). Most investigators conduct their tests in the frequency range of 5 to 30 Hz, a range that would most likely prevent time-dependent, corrosion-related mechanisms from having an important effect. Frequency can be considered of secondary significance as an experimental variable for investigation.

Criteria for evaluation of fundamental fretting fatigue experiments should be expanded to include crack propagation and trajectory studies, in addition to fatigue life degradation. Though extremely difficult to study experimentally, information could be gained relating to contact conditions in the early crack growth stage while the crack is in the contact stress field. Crack length measurement (possibly necessitating specimen sectioning) under sequential fretting fatigue exposures would be needed. From data on the rate and direction of crack growth, local stress intensity levels can be deduced. Also surface damage features leading to propagating and nonpropagating cracks might be identified and clarified. The experimental work should be coupled with analytical modeling efforts if progress can ever be made toward developing reliable tools for predicting fatigue life under fretting conditions.

# APPENDIX

# LITERATURE APPRAISAL

## A. INTRODUCTION

The objective of the Literature Appraisal is to focus on the task before the Committee on Control of Fretting-Initiated Fatigue of the National Materials Advisory Board as outlined in the Executive Summary of this report. The comments in the Literature Appraisal are brief; selected studies are examined more extensively in Chapters 1 through 4 of this report.

The Recon Literature Search Facilities of the NASA-Lewis Research Center (201) were utilized to explore U.S. Government sources for current reference information on fretting-induced fatigue and related topics.

The Smithsonian Science Information Exchange generated an off-line citation list using ORBIT III, on the topic of fretting that included 18 items.

To assure coverage of international and especially European titles on technology relevant to fretting-induced fatigue, the assistance of Professor Dr. -Ing K. Kirschke, Bundesanstalt für Materialprüfung [Federal Institute for Testing Materials (BAM)], 1 Berlin 45 (Dahlem) Unter den Eichen 87 was enlisted. Professor Kirschke and his associates at BAM compiled a notable continuing annual subscription series of "Documentation - Wear, Friction and Lubrication," Volumes 1 through 11 (107). Professor Kirschke suggested 307 items.

For additional international coverage, Tribos, Tribology Abstracts, published by the British Hydromechanics Research Association at Cranfield, Bedford (MK 43 OAJ), England was scanned.

A substantial list of references has been compiled. Many of them are of only peripheral interest to the problem at hand. There were duplications in the source lists and, therefore, all references are listed alphabetically in the Bibliography. Reprints of the references cited in this report were obtained through the library facilities of Rensselaer Polytechnic Institute and NASA-Lewis Research Center. Mr. Louis Scarselletta of R.P.I. participated in document review to establish specific relevance.

One element of conflicting understanding is found in many of the documents; that is, the consideration of fatigue as a wear mechanism that produces fretting wear debris or as a structural failure mechanism. Clearly, the final structural failure must be avoided, and the role of fretting (by all wear mechanisms if relevant) on inducing the structural failure is the problem that must be resolved.

The problem background providing motivation for the present effort is considered essentially that which led to the recent AGARD Symposium on fretting in aircraft systems (1).

A comprehensive review of fretting fatigue literature was made in the industry-sponsored Fracture Control Program of the College of Engineering, University of Illinois and is reported by Yeh and Sinclair (209) which contains sixty references included in this study.

In this program, a preponderance of evidence indicates that fretting fatigue is primarily a mechanical rather than a chemical problem. The process involves two stages: (1) a crack initiation stage wherein small cracks are formed at regions of stress concentration near cold weld junctions and (2) a propagation stage wherein the minute cracks may be propagated to failure by the fluctuating nominal stress.

The prime variables controlling these processes are (1) the surface hardness or yield strength of the materials in contact, (2) the contact pressure and (3) the coefficient of friction between the two. Increasing surface hardness or yield strength, decreasing contact pressure and reducing the coefficient of friction all tend to reduce the "initiation" crack size and consequently improve fretting fatigue strength. Surface compressive residual stress fields can stop or retard early propagation of these cracks and, thus, also increase fretting fatigue strength.

Case studies of successful "fixes" of fretting fatigue problems are neither numerous nor well documented; nevertheless, all appear to involve application of one or more of the aforementioned principles. Specific methods of improving strength vary widely in cost and effectiveness, each possesses its own special characteristics and drawbacks and, in general, the method selected is determined by the service conditions. Suggested methods of improving fretting fatigue strength are as follows:

## 1. Induce Surface Compressive Residual Stress

All methods commonly employed to induce surface compressive stress also produce increased surface hardness and, thus, provide a twofold benefit.

- Shot Peening is reasonably effective and relatively incxpensive. It produces a shallow, work hardened, compressive surface layer which, on small components, can recover up to 50 percent of the normal strength loss due to fretting. Typical results [Bowers, et al. (27)] are shown in Figure A-1.

- Surface rolling with hardened rollers produces results similar to shot peening but is far more expensive. It is used when extra penetration and compressive layer depth are required, as in larger shafts and components. The effects of surface rolling can penetrate to one-quarter inch or more below the surface. Some typical results for surface rolling [Sachs and Horger (152)] are given in Figure A-2.

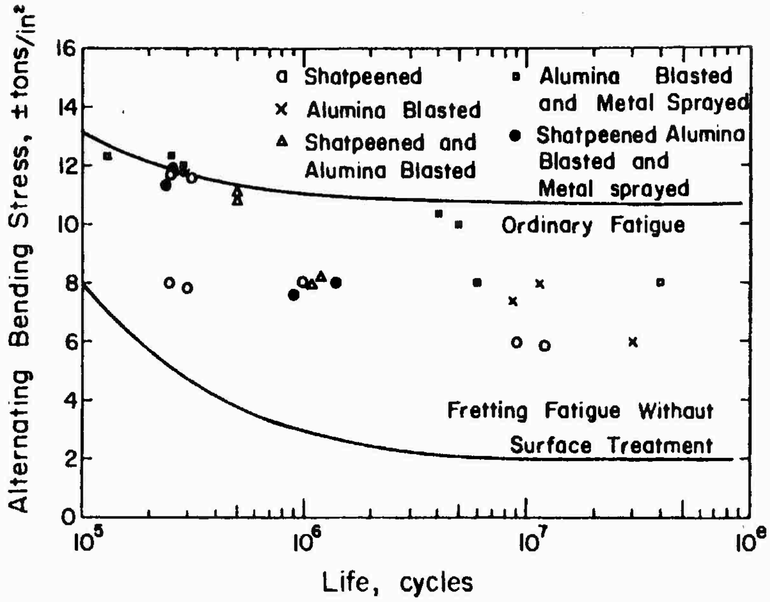



FIGURE A-1 The Effect of Shot Peening, Alumina Blasting and Metal Spraying on the Fretting Fatigue Strength of DTD 683. [Reproduced from (27) by permission of the Council of the Institution of Mechanical Engineers.]

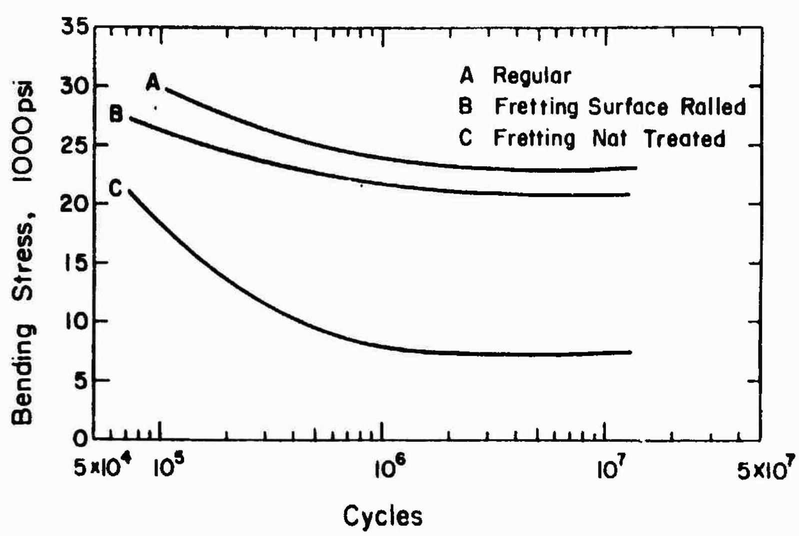



FIGURE A-2 Stress Cycle Curves for Regular Fatigue and for Fretting Fatigue of Surface-Rolled and Untreated Specimens of Magnesium Alloys (152)

- Nitriding or carburizing followed by quenching can produce a shallow, very hard, wear-resistant surface layer which is compressively stressed. It should be quite effective in raising the fretting-fatigue strength of small components, but convincing documentation is lacking.

- Surface induction hardening will produce results similar to carburizing in a much deeper surface layer. It should be better for larger components. While industrial application to fretting problems is common, quantitative data is lacking on expected improvement.

## 2. Tensile Prestrain

Tensile prestrain accompanied by fretting produces a shallow compressively stressed surface layer in the fretted region. Laboratory results (Collins and Marco, 38) show that the metal retains nearly 90 percent of the original fatigue strength but it must be noted that the layer is very shallow and would eventually be worn away.

## 3. Shims

Sacrificial, soft metal shims or inserts of commercially pure aluminum or magnesium between the normal contacting surfaces can leave the the fatigue strength at 95-100 percent of its normal value. The drawback to this technique is that the soft metal is fretted away and must be replaced periodically.

## 4. Lubrication

Lubrication to reduce the coefficient of friction ranges widely in effectiveness depending on the character of the lubricant. Improvement in fretting fatigue strength due to treatment with oils or greases ranges from zero to only a few percent. The high-viscosity materials seem to do best but, in any event, improvement is only marginal. Some results for the lubrication of steel surfaces in contact, such as those summarized in Figure A-3, appear significant until the stress scale is examined more carefully. Here, the normal scatter to be anticipated in long-life fatigue strength would occupy much of the range shown.

Dry lubricants, such as molybdenum disulphide, are better able to resist high contact pressure, and improvements of up to 20 percent in fretting fatigue strength have been reported.

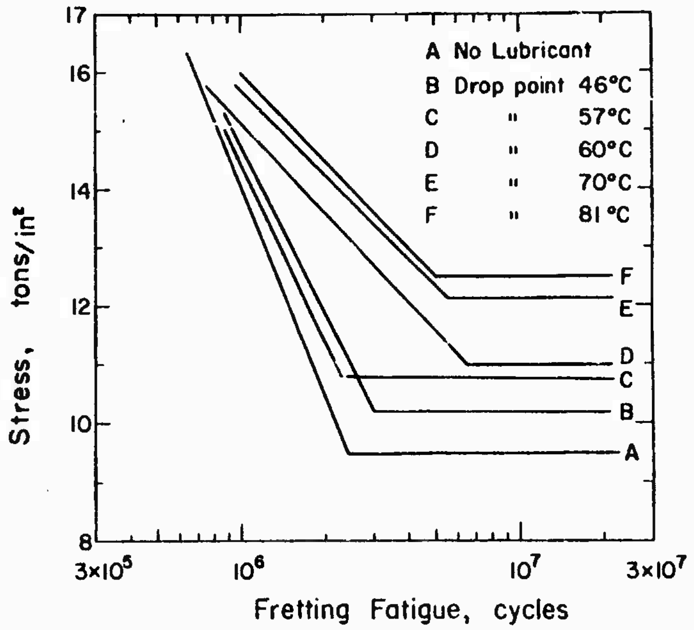



FIGURE A-3 Fretting-Fatigue Curves for the Rubbing Steel Lubricated with Commercial Lubricants. [Reproduced from (196)].

5. Special Surface Coatings

Special surface coatings remain a relatively unexplored area. Under relatively low contact pressures (1000 psi), Teflon coating produces good results until the Teflon is worn through and contact of the base metals occurs. Thin coatings of soft metals such as aluminum provide little improvement in fretting-fatigue strength as they quickly wear away, although some improvement following spraying with an aluminum--one percent zinc alloy in combination with shot peening (Figure A-1) was shown by Bowers, et al. (27). Hard metal plating (chromium) and flame spraying with tungsten provide little improvement in fretting-fatigue strength. While the wear rate is reduced by these coatings, they apparently contain many surface fissures which soon lead to crack growth in the base metal. One exception to this experience with hard metal coatings is shown in Figure A-4 where a significant improvement in strength accompanied molybdenum coating.

B. PROBLEM DEFINITION

At the Advisory Group for Aerospace Research and Development (AGARD) Conference held in Munich, Germany in the fall of 1974, a series of papers

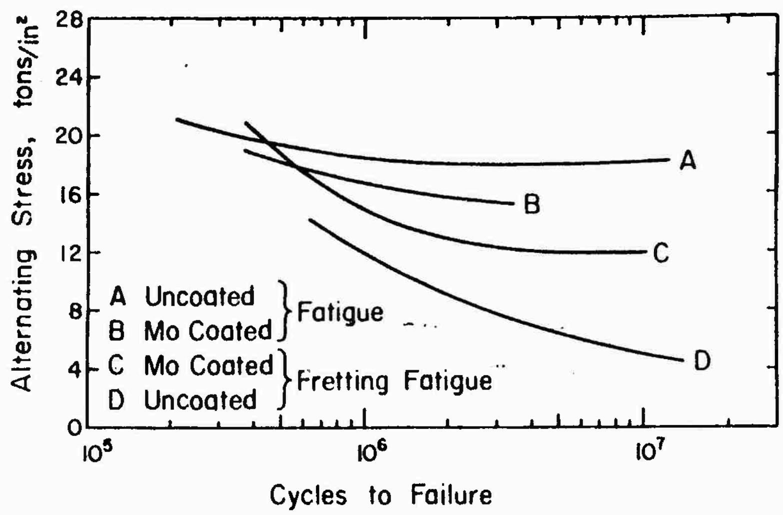



FIGURE A-4 Fatigue Curves for En 8 Steel with and without Mo Coating and with and without Fretting (172).

devoted to the problems of fretting and fretting-induced fatigue in aircraft systems were presented (1). The discussions on aircraft control surfaces, the structures, helicopters in particular, and also in the drive train components of both jet aircraft and helicopters showed the concerns that fretting and fatigue were indeed very difficult problems. The basic mechanism of fretting and fatigue comprises a sequence of events including superposition of applied dynamic stresses on the residual tensile stress fields. Fretting cracks are frequently observed to originate in the boundary between the slip and nonslip regions. Temperature rises in the contact zone can lead to thermo-electric effects between dissimilar metals and to metallurgical effects which make work-hardened and age-hardened alloys particularly susceptible to fretting damage. Also, for copper alloys in contact with steel under lubricated conditions, sliding wear is shown to be an estimate of the fretting potential. Finally, papers on the role of lubrication under extreme pressure were presented at this Conference. The formation of anti-fretting products on the surface to separate the surfaces in contact with high shear stability and low friction was shown to be important. In particular, attention is directed to papers by J. R. Lee (1c) on fretting in helicopters; fretting in aircraft turbine engines by R. L. Johnson and R. C. Bill (1e); the influence of fretting on fatigue by W. J. Harris (1g); and the fretting of aircraft control surfaces by D. W. Hoeppner (1a). Other papers presented at this Conference are cited in other sections of this chapter.

Goss and Hoeppner (74) show that the scanning electron microscope is a useful tool in the analysis of fretting damage. In the examination of specimens

which have undergone simultaneous fretting damage and fatigue, the SEM study indicated that irreparable or catastrophic damage is not produced during the early cycles of fretting which suggests that fretting can be repaired in its early stage. It was also observed that the damage produced during fretting fatigue tests had very consistent characteristics with either high or low fatigue stress, suggesting that the fatigue stress loading is a minor consideration in the progression of fretting wear; however, it would be far more significant in regard to the determination of the fretting-induced fatigue life.

Field (62) reports some studies on the effect of the direction of fretting on the fretting fatigue strength of an aluminum alloy. That study showed that the fretting movement applied in the direction of the fatigue stress resulted in a much greater reduction in the fatigue strength than when the fretting movement was applied transverse to the direction of the fatigue stress.

Goss and Hoeppner (75) reveal that titanium and aluminum alloys behave quite differently in fretting fatigue under similar normal pressure conditions. The aluminum appears to be insensitive to load changes. On the other hand, the life dependence of the titanium is very sensitive to the normal pressures in the fatigue process. This difference is explained in terms of local crystallographic effects and microvariations in toughness of the two materials.

Hoeppner and Goss (89) indicate that a fretting fatigue damage threshold results from the fretting that was found to exist for both titanium and aluminum alloys. At all load levels, a given amount of fretting damage is required before any fatigue life reduction occurs. Presumably, the damage leads to the development of cracks in the fretted areas. The concept of the fretting damage threshold is related to the development of an initial crack that causes the local stress intensity to exceed the threshold value at a much smaller number of applied cycles. Thus, the concepts of fracture mechanics are related to the initiation of fretting damage.

Reference 127 summarizes the nature of fretting and then describes the effect of fretting on fatigue. Of special note in this Literature Appraisal is the statement to the effect that fatigue strength of mild steel was reduced to one fifth where there was fretting as part of the use process. Differences were noted between the behavior of mild steel and harder steel and these differences were considered to be ascribable largely to differences in crack propagation characteristics of the two types of steels.

In Stowers and Rabinowicz (167), the authors explored the mechanisms of fretting wear both in an analysis of literature information and in some quantitative fretting wear studies. These results suggest that the material loss more closely resembles that produced by unidirectional adhesive wear than material loss produced by other types of wear. The study also indicated that the amount of wear may be computed by the use of Archard's equation.*

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* To a first approximation, wear rate is directly proportional to load and inversely proportional to hardness.

Although not carried to the point of fatigue structural problems, the reference data of Swikert and Johnson (170) suggests that the fretting conditions which occur in aircraft turbine compressor blading can introduce problems of vibrational stresses which will increase as the progression of fretting occurs. This, of course, would accelerate any tendency toward fatigue with the increasing vibrational stresses on the rotating element.

Rollins and Sandorff (148) reported photoelastic investigations of the stress environment occurring in contact with fatiguing structures such as the surfaces of damped, or bolted and clamped double-lapped joints which carry appreciable amounts of load in friction. It was pointed out that slippage occurs in such joints with the first application of load, initiating at the extreme edge. The line of distinction between the slipped and unslipped regions is called the "slip front" and moves lengthwise along the joint as load is increased. The slip is believed to be a primary cause of fretting in joints and, therefore, is considered a significant factor in fatigue strength.

Harris (80) again pointed out the fact that the low fatigue efficiencies often displayed by bolted joints and similarly fastened design elements is attributed to the potency of the fretting fatigue mechanism. He proposes to eliminate fretting damage of a simple bolted strapped joint by the treatment of the contact surfaces.

Duquette (46) reviewed the problem of fretting-induced fatigue. This compilation of data from other sources concluded that due to controversies and a lack of consistency in the knowledge of this area, further study is mandatory.

Golego, et al. (72) presented the results of investigations of fretting by the Kiev Civil Aviation Engineers Institute in Russia. This study made it very clear that the service life of aviation parts and mechanisms are very often limited by fretting-induced phenomena both within the airframe and within the aviation engine. The authors point out the very substantial influence of the corrosive or reactive environments and also that there are a great many fatigue microcracks that are part of the fretting process. It also indicates that if a surface is subjected to a sufficiently rapid fretting wear, the crack propagation is arrested and the fatigue wear process is initiated again without the development of structural fatigue cracks.

Filemonov, et al. (65) reports Russian work showing that the fretting processes present the greatest danger to shafts affixed to screw propellers in casings by press fitting. When shafts are subjected to surface plastic deformation in press-fitted joints, it appears possible to prevent higher working stresses. Presumably, the substantial interference reduces the likelihood of fretting wear. Working with shafting of 200 millimeters in diameter, the authors make clear that there are substantial benefits which can be gained by the process of work hardening of the surface prior to operation. It is apparent from this and other referenced studies in this report that the Russians are substantially concerned with the fretting-induced fatigue problem in heavy-duty shafting for naval operations in particular.

In his book, Fretting Corrosion, R. B. Waterhouse (187) treats many o. the concerns in fretting, and includes fretting and fatigue characterization in Chapter 8. The book is a very good summary reference and includes many of the considerations of other references cited in this presentation.

In this section on Problem Definition, it is well to mention the extensive work of Nishioka, Nishimura and Hirakawa (86 and 121-125). They provide some food for thought in their viewpoints on the primary effect of the stress field rather than fretting wear as the origin of fretting-induced fatigue.

A study in The Netherlands National Aerospace Laboratory (182) shows that fretting did have an effect on the fatigue life at low, as well as high, loads for pin-loaded loosely fitting lugs of 2024 T-3 aluminum alloy. The interactions of clamping and lubrication were found and recommendations made for future experimental studies.

R. C. Bill (25) shows that the fretting phenomenon varies greatly with different alloys and that the structure of the alloys plays an important part. Of greater significance, the observation was made that the ratio of oxide hardness to metal hardness was a measure of the susceptibility of a metal to progressive damage by fretting.

In summarizing the problem definition considerations in this Literature Appraisal, it is apparent that a very substantial difference in problem concept is prevalent among the various investigators. It is not always clear if fretting wear is a driving factor with regard to the initiation of fretting-induced fatigue or whether fatigue is simply a result of the complex stress fields that are created by the presence of a fretting surface. The initiation of fretting-induced fatigue depends very substantially on the characteristics of the different metal alloys. Those characteristics include the metallurgical structure, the oxidation properties, the state of working (i.e., the residual stresses that may result from cold working) and the susceptibility to heat treating of the alloy under consideration. While the problem of fretting-induced fatigue is very often cited for aerospace applications where light structures allow substantial deformation, it also occurs in very heavy industrial and marine applications and so becomes a rather universal problem.

## C. FUNDAMENTALS

Hurricks (99) provides an excellent review of the fretting phenomenon. There are three widely accepted progressive stages of fretting: (1) the initial adhesion and metal transfer; (2) the production of debris in a reactive state: and (3) the steady-state wear condition that can be adhesive, abrasive, corrosive and fatigue. The geometry of the fretting part and the properties of the debris have much to do with the manner by which steady-state wear condition progresses because of debris retention or removal. The Hurricks paper cites

a number of references and discusses the various theories of fretting and provides a good basis for information to the investigations of fretting. The book by Waterhouse (187) also serves very well in this regard.

Reference 1 presents a number of papers on the fundamentals of fretting, including notable papers by Waterhouse, Godfrey, Beglinger and DeGee, and van Leeuwen.*

The strong influence of ambient temperatures from 200°C to 500°C on the fretting of mild steel is demonstrated by Hurricks (98). The oxide films produced on steel at the increasing temperatures caused fretting wear to continually decrease up to 500°C. This observation again shows the very marked importance of protective surface films formed by reaction with the environment of operation. In this regard, it is well to consider Bill (25); this study suggested that the ratio of oxide hardness to metal hardness was a measure of the susceptibility of a metal to progressive damage by fretting. Stowers and Rabinowicz (167) established a correlation between the wear coefficient and the friction coefficient in fretting wear.

Waterhouse (191) indicates that, in the fretting process, fatigue cracks are initiated as the result of local high stress. The most informative method of investigating the effect of fretting is the use of a two-stage test which gives a means for determing the number of fretting cycles needed to initiate a fatigue crack.

Ohmae and Tsukizoe (131) indicate that, at small slip amplitudes, fretting oxidation (a mild type of wear) occurs; with larger slip amplitudes, adhesion and abrasive wear occur together with oxidation as the cause of fretting wear. With still larger amplitudes, wear similar to reciprocating sliding wear occurs.

Endo, et al. (51) uses the model of a spring system to analyze the relation between the tangential force and relative slip displacement under fretting fatigue conditions. The damaged layer of steel due to fretting fatigue was studied for stress conditions near the contacting surface and related to this mathematical model. This reference is basically a testing of a mathematical model.

Harris (lg) suggests that there is strong supporting evidence for the high significance of residual tensile stress fields generated by the plastic deformation of the compressed asperities in the fretted areas. Experimental evidence indicates that fretting fatigue failures may, with equal probability, be nucleated just within or without the fretting scar profile. It should be mentioned also that Yeh and Sinclair (209), cited earlier, includes a substantial discussion of the mechanisms of fretting fatigue.

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* van Leeuwen is a discussant of Paper lm.

The seven important variables that influence fretting fatigue are discussed in Yeh (208) which proposes a hypothesis to estimate fretting fatigue strength. Two sets of experimental data on long life fretting-fatigue strength are compared with predicted values resulting from the hypothesis. The predicted values and the experimental results are found to be in good agreement and are presented in graphical form.

The studies of Hirakawa and associates (86) and (121-124) bear special mention because they showed the reduction of fatigue strength is mainly attributed to the stress concentrations caused by the frictional force due to fretting. The fatigue cracks are located in the stress concentration volume. Those cracks show inclinations to the surface and the directions of these cracks can also be explained by the contact stresses. The cracks grow in the direction perpendicular to the maximum principal stress in the fretting area.

Roberts (146) reviews the effect of contact geometry on fretting fatigue and concludes that there are two fretting fatigue theories that most accurately fit the situation: first, the formation of microscopic cracks by asperity contacts; and, second, growth of these cracks under local macroscopic stresses up to a size which can propagate under the applied cyclic stress.

David W. Hoeppner and Hoeppner and Goss have published a number of papers on the mechanisms of fretting fatigue. Reference 93 examines the surface damage produced under fretting fatigue conditions for a given material at several stress levels. The authors discuss those results in the light of a number of theories of fretting and fretting fatigue and conclude by developing a schematic representation of a model for fretting fatigue.

Substantial contributions to the fundamental considerations of fretting-induced fatigue are contained in (74), (75), (89), and (92). In (92), an analysis of fretting in titanium and aluminum alloys, it was found that a given amount of fretting damage was required before any fatigue life reduction occurred. Presumably, the damage leads to development of cracks in the fretted area, multiple cracks form and are propagated by fatigue. The fretting debris is forced into microcracks as they develop and could explain, in part, the significant reduction in life caused by fretting in its effect on fatigue, although recent measurements suggest that the crack tip opening displacement range is reduced in the case of infiltrated cracks, which could reduce the rate of crack growth. It was pointed out that a larger number of secondary cracks are produced in the fretting region of laboratory fretting fatigue specimens. Also, the cracks produced in fretted regions differ in character as a function of applied fatigue stress. These observations lend further support to a fretting fatigue damage concept related to mechanical action between the contacting surfaces.

## D. DESIGN APPROACH

Almost every positive action described in the Problem Identification and Fundamentals chapters of this report can be utilized to develop improved design approaches. These approaches involve materials, surface films and lubrication, and also mechanical approaches that deal with the control of the stress field in the suspect application. A compendium of such information is present in Fretting Corrosion (187). It should also be noted that the AGARD symposium (1) includes considerations by P. M. Ku,* R. J. Benzing, G. Salomon,** and V. von Tein all pointing to design approaches.

Many of the fretting problems result from misalignment of mechanical devices such as splines, and it is obvious that designs should be such that the misalignment would be at the very minimum practical level. Utilizing design approaches to eliminate fretting per se are, of course, of basic importance to the elimination of fretting fatigue. It is clear that in the materials approach to fretting fatigue mitigation, only certain polymers have been demonstrated to be effective in combating fretting. Possibly, the composite concept of mitigating fretting can be extended to the case of organic bonded solid lubricant films. Since the early work of Godfrey, the use of molybdenum disulfide as a fretting inhibitor has been widely recognized and practiced in many engineering applications. Present advanced solid lubricant films include one, designated as AFSL-41, suggested by Benzing at the AGARD meeting. It includes the silicone resin as a bonding agent for molybdenum disulfide and has been found effective in reducing fretting of titanium engine compressor components. At the AGARD Conference, W. J. Harris (lg) pointed out that the beneficial effects of induced compressive stress by cold working techniques like shot peening on conventional fatigue strength are also available for improving fretting fatigue behavior. Anti-fret treatments include both anodizing and induced residual stress.

R. C. Bill (23) reported studies of nickel alloys which showed better fretting resistance for alloys than for pure nickel. This was due to the oxide coatings which formed on the alloys, e.g., increased aluminum concentration reduced fretting wear at all temperatures. Liu, et al. (110), in an article on the fatigue strength of titanium alloy, indicated ways of mitigating the effects of fretting-induced fatigue. It pointed out that special surface treatments employing either an oxidized layer or Teflon coating increased the fretting fatigue strength to approximately 0.56 of the fatigue limit for the alloy. The layers were used to prevent metal-to-metal contact and to reduce the coefficient of friction. Surface treatments which did not reduce

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* Ku is a reference source of Peterson and Ling (11)

** Salomon is a reference source of Franceschini (lo)

friction, such as carbide plating and aluminizing, did not have beneficial effects on fretting fatigue life. With this particular alloy of titanium, the exclusion of oxygen or air atmosphere did not result in improved fretting fatigue strength. However, it must be remembered that titanium is extremely reactive and the partial pressure of oxygen necessary for protection is very low.

Yeh (208) also discussed various methods of minimizing fretting fatigue damage. Harris (80) made a plea for providing a meaningful anti-fretting design that considers fretting fatigue both as a phenomenon of failure by simultaneous action of dynamic stresses and a friction wear process. Emphasis is placed on the use of close tolerances dealing with joint design, proper bolt torques, dimensional tolerances, etc. needed to provide anti-fretting designs.

Ohmae, et al. (129) dealt with the fretting between carbon fiber reinforced plastics and mild steel. The use of such composites is of particular significance for advanced aircraft where there will be increased use of reinforced plastic composites. This material has a high degree of tribological anisotropy. The best resistance against fretting was found when the steel specimen slid in a direction parallel to the unidirectionally oriented carbon fibers and within a region of about 30° from the carbon fiber axis. Therefore, it is clear that the wear volume was significantly influenced by slip orientation. Sandifer (155) indicated that fretting has no significant effect on the fatigue life of graphite/epoxy material when fretted against an aluminum alloy, titanium or the same graphite/epoxy composite material.

In (154), Sandifer dealt with the widely varying fatigue strengths of aluminum lap joints, depending upon the types of treatments applied to the surfaces. The evaluation found the best methods (in order of effectiveness) to increase fatigue strength were: bonded and shot peened; bonded alone; shot peened alone; and bonded steel wear pads. The investigations were concerned only with bolted joints.

Overd (132) reported a 1958 study on fretting fatigue tests of pin joints. The author showed the effects of anodizing, plating, surface finish and various joint compounds for both light alloy and steel lugs. The most beneficial treatments involved the use of $MoS_2$ anti-scuffing paste, and lithium stearate grease on the L-65 aluminum alloy. For the steel lugs, aluminum disulfide anti-scuffing paste was also found beneficial, cadmium plated bores were effective, as was zinc plating of the bore and pin. A variety of surface treatments, including the use of several commercial molybdenum disulfide products, case hardening, and graphite were found to have questionable utility. The use of molybdenum disulfide was not completely beneficial in the Saunders-Roe, Ltd. extended program and, in fact, in some combinations the use of molybdenum disulfide was found to be harmful. The use of $MoS_2$ as a paste with lithium stearate grease was found to be useful with the L-65 aluminum alloy.

Ivanova and Veitsman (100) described some relatively old work in Russia where the mating surfaces of the metal parts were coated with nairit. Nairit is a variety of synthetic rubber which can be applied by simple industrial processes. For steel and aluminum parts, the prevention of fretting corrosion by frictional phenomena increased the cyclic or fatigue strength of the components to a very great extent.

A materials-oriented article is Kauger (104) which describes the characteristics of fretting failures, the fundamentals of fretting, and the recognition, prevention, and examples of failures due to fretting. It is not a particularly significant reference with regard to fretting fatigue failure but must be considered for its completeness. Nishioka and Hirakawa (123) indicated that the fatigue limit for fretting-induced fatigue can be raised by induction hardening of steel.

Ohmae, et al. (130) reported some work on the use of ion plated films to inhibit fretting. Ion plated boron carbide films showed the best resistance to fretting. The article also pointed out that the better adhesion of ion plated films as compared with other types of vacuum-deposited and commercial methods was considered to be the factor giving better wear resistance in the fretting process.

Wharton and Waterhouse (200) reported the fretting fatigue strength of an aluminum alloy in contact with pads of aluminum, copper, 70/30 brass and 0.7 carbon steel. The steel and aluminum pads produced reductions of 34 percent and 28 percent respectively. The effect of fretting on fatigue strength is explained in terms of the added shear stress arising from the frictional force between the pad and the specimens. Although the coefficient of friction is initially low, it rises after 500 to 1,000 cycles of fretting and then remains relatively constant.

Waterhouse (187) mentioned that at equal maximum stresses, a superimposed stress ripple is detrimental to the fatigue life of a pin-loaded lug under a crenellated fatigue load and becomes more so with higher amplitudes of the ripple. The application of an anti-fret coating can remove the effect of the ripple and increase the fatigue endurance per se. Application of a moderate clamping pressure can be far more effective because it promotes load transfer by friction rather than by bearing stresses. At a moderate clamping pressure, the added effect of an anti-fret coating is detrimental rather than beneficial because it reduces friction. In the absence of an anti-fret coating, an increased clamping pressure is not beneficial at high fatigue loads because it promotes fretting in the clamped area. Under severe fretting conditions due to a high fatigue load and increased amplitude of the ripple, the combination of an anti-fret coating and the high clamping pressure proved to be more beneficial than each of these separately. The anti-fret coating, like the graphite grease, can be effective under moderate bearing pressures in the clamped area but is still ineffective under the high bearing pressures between the pin and whole wall.

Superiority of the anti-fret coating over graphite grease can be observed at high clamping pressures, but is rather limited. Reinforcement of the anti-fret coating with a fabric may increase its effectiveness. The anti-fret coating referred to is a system including graphite flakes in a cold setting resin.

Hirakawa, et al. (86) evaluated the effects of size, shape, clamping pressures, magnitude of nominal stresses and number of cycles and frequency of alternating stresses on the incidence of fretting-induced fatigue in press-fitted axle assemblies.

In summation, this section reveals that a myriad of approaches have been suggested and have found merit with regard to the selections of materials, surface films and lubrication, and also design variations. It is very likely that the wide variety of conditions and applications would mean that a systems analysis approach would be needed to resolve the differences in successes with these various devices to mitigate fretting fatigue.

## E. EVALUATION METHODS

The Special Technical Publication, Evaluation of Wear Testing (53) is a publication of the American Society for Testing and Materials (ASTM) on evaluation of wear testing. It covers a variety of systems including some applicable to the fretting problem. Additionally, the Fundamentals Committee of the American Society of Lubrication Engineers (8) have compiled a catalog of friction and wear test devices. These are assembled on the basis of specimen configuration but include many that have proved useful in studying fretting. In those and other summary compilations, as well as Waterhouse (187), much attention is given to fretting and little to problems of fretting-induced fatigue. In some cases, for example, Nishioka and Hirakawa (121), the apparatus is designed primarily to determine the slip amplitude or other factors in a typical mechanical device such as the pressed-fit surface between the hub and the axle. The Lockheed-California Company at its Rye Canyon Research Laboratory developed a new apparatus for studying fretting fatigue which is described by Hoeppner and Goss (90). This device allows the fretting and fatigue processes to occur simultaneously. The apparatus continually monitors loads in the hope that quantitative relationships can be developed relating fretting damage to life. Table A-1, quoted from (90), is a summary of apparatus previously employed by other investigators for fretting and fretting fatigue studies.

In (182), van Leeuwen, et al. reports the modification of an electro-hydraulic fatigue machine for the evaluation of fretting fatigue. This device provided for the superposition of a rectangular or crenellated wave form for low frequency fatigue load on which a high frequency, low amplitude sinusoidal load ripple could be superimposed at will. The report, Notes on the Influence of Fretting on Fatigue (127), also shows the test configuration that involves cyclic load in tension for the fatigue test component.

TABLE A-1 Apparatus Previously Employed for Fretting Fatigue Studies

| Reference | | Material | Machine Type |
|---|---|---|---|
| (1) | D. Godfrey, "Investigation of Fretting by Microscopic Observation," NACA Rep. 1009 (1951). | Metal and glass | Spherical ball against glass or metal flat and displaced. Environment and temperature controlled. |
| (2) | A. J. Fenner, K. H. R. Wright and J. Y. Mann, "Fretting Corrosion and Its Influence on Fatigue Failure," Proc. Int. Conf. Fatigue of Metals, (1956), pp. 386-393. | Aluminum on aluminum | Direct stress, no environment control. |
| (3) | H. W. Liu, H. T. Corten, and G. M. Sinclair, "Fretting Fatigue Strength of Titanium Alloy RC130B." Proc. ASTM 57, 623 (1957). | Ti RC130B against various materials | Bending fatigue. |
| (4) | W. L. Starkev, S. M. Marco, and J. A. Collins, "Fretting Fatigue Damage of Titanium and Steel," Machine Design 30, Part 1. 140 (1958). | Titanium against steel | Rotating beam fatigue machine modified to produce fretting between specimen and special collet. |
| (5) | E. Gassner, "On the Influence of Fretting Corrosion on the Fatigue Life of Notched Specimens of an Al-Cu-Mg 2 Alloy," Fatigue of Aircraft Structures (May, 1961). | Al-Cu-Mg alloy against steel | Shenck direct stress with special arrangement for producing fretting at the root of a notch. |
| (6) | J. A. Collins and S. M. Marco, "The Effect of Stress Direction During Fretting and Subsequent Fatigue Life," Proc. ASTM 64, 547 (1964). | 4340 on 4340 | Krouse direct stress fatigue machine. |
| (7) | W. D. Milestone, "A New Apparatus for Investigating Friction and Metal-to-Metal Contact in Fretting Joints," Effects of Environment and Complex Load History on Fatigue Life, ASTM STP 462 (1970). pp. 318-328. | 7075-T6-Al and Ti 6Al-4V against same material | Flat plate reciprocating bending fatigue with normal load application. |

In summary, there are very few details available on the devices that are utilized as test equipment. It is very clear that the experimental devices showing attractive applicability involve imposing the fretting test onto a typical fatigue experiment. Tension fatigue specimens are most commonly used; however, bending fatigue specimens have also been employed. They introduce some problems with defining the contact area of the fretting components. However, there are many cases where bending fatigue probably more closely approximates the application than do straight tension experiments.

## F. CONCLUDING REMARKS

This Literature Appraisal on fretting-initiated fatigue indicates that the research programs in fretting-induced fatigue are rather limited and, to some extent, the literature is contradictory. There is need for modern, well-planned studies to explore contradictions and seek understanding and solutions for the fretting-initiated fatigue problem.

# BIBLIOGRAPHY


1. AGARD (Advisory Group for Aerospace Research and Development), Specialists Meeting on Fretting in Aircraft Systems, AGARD Conference Proceedings No. 161, Fretting in Aircraft Systems, January 1975, Papers presented at the 39th Meeting of the Structures and Materials Panel, Munich, Germany, October 6-12, 1974. See especially:

   a. Hoeppner, D. W., "Fretting of Aircraft Control Surfaces," pp. 1-1 - 1-7.

   b. von Tein, V. and P. E. Seibert, "Fretting of Structures for Modern V.G. Fighters," pp. 2-1 - 2-13.

   c. Lee, J. R., "Fretting in Helicopters," pp. 3-1 - 3-8.

   *d. Salkind, M. J., "Fretting Fatigue in Titanium Helicopter Components," pp. 4-1 - 4-5.

   e. Johnson, R. L. and R. C. Bill, "Fretting in Aircraft Turbine Engines," pp. 5-1 - 5-13.

   f. Thiery, J. and Spinat, R., "Comment Reduire L'Usure des Pieces Non Lubriefiees dans les Turbomachines," pp. 6-1 - 6-14.

   *g. Harris, W. J., "The Influence of Fretting on Fatigue," pp. 7-1 - 7-11.

   h. Waterhouse, R. B., "Physics and Metallurgy of Fretting," pp. 8-1 - 8-8.

   i. O'Connor, J. J., Discussion of above paper, pp. 8-9 - 8-13.

   j. Begelinger, A. and A. W. J. deGee, "Surface Distress of Copper Alloys in Contact with Steel under Fretting Conditions," pp. 9-1 - 9-7.

   k. Deyber, P. and M. Godet, "La Lubrification Extreme-Pression," pp. 10-1 - 10-12.

   l. Peterson, M. B. and F. F. Ling, "Design of Pivots for Minimum Fretting," pp. 11-1 - 11-12.

   m. Gonin, A., A. Berger and J. J. Caubet, "Nouvelles Possibilities Offertes per les Traitements de Surface," pp. 12-1 - 12-15.


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* Indicates documents directly related to fretting-induced fatigue.

n. Buckley, D. H., "Effect of Various Material Properties on the Adhesive Stage of Fretting," pp. 13-1 - 13-15.

o. Franceschini, A., "Self-Lubricating Polymers," pp. 14-1 - 14-14.

p. Benzing, R. J. and B. D. McConnell, "Fretting Wear Behavior of a Polysiloxane Bonded Solid Lubricant," pp. 15-1 - 15-5.

q. Godfrey, D., "Fretting Wear of Steel in Lubricating Oils," pp. 16-1 - 16-6.

2. Abrahamson, E. P., Coatings for Wear Resistance, U.S. Army, Materials and and Mechanics Research Center, Watertown, Mass., July 1974.

3. A Guide for Fatigue Testing and the Statistical Analysis of Fatigue Data, American Society for Testing and Materials, Special Technical Publication (STP) No. 91A, Second Edition, 1963.

4. Allsop, R. T., "Fretting Corrosion of Metals," Metallurgia (The British Journal of Metals), 60, pp. 87-92, 1959.

5. Alyab'ev, A. Ya., V. V. Shevelya and V. P. Onoprienko, "Variation in the Electrode Potential of a Metal During Fretting Corrosion," Soviet Materials Science, 9, pp. 17-19, 1973.

6. Alyab'ev, A. Ya., V. V. Shevelya and M. N. Rozhkov, "A Criterion of Wear Resistance with the Fretting Corrosion of Metals," Soviet Materials Science, 8, pp. 502-504, 1972.

7. Alyab'ev, A. Ya., V. V. Shevelya and D. A. Shcherbina, "Energy Analysis of Fretting Corrosion," Soviet Materials Science, 6, pp. 591-595, 1970.

8. American Society of Lubrication Engineers Fundamentals Committee, Friction and Wear Devices, Second Edition, American Society of Lubrication Engineers, 1976.

9. Anon., "Ion Implantation - A Technique in Wear Research," Industrial Lubrication and Tribology, p. 193, 1975.

10. Anon., "Procedure of Calculation of Nominal Elastic Interface Pressure and Stresses in Assembly of Three or More Elements," Engineering Sciences Data, Mechanical Engineering Series, Part 3, Institution of Mechanical Engineers, London, 1968.

11. Annual Book of ASTM Standards, Part 10, American Society for Testing and Materials, Philadelphia, Pa., 1975.

12. Archard, J. F., "Contact and Rubbing of Flat Surfaces," J. Applied Physics, 24, pp. 981-988, 1953.

13. Archard, J. F., "Wear," Interdisciplinary Approach to Friction and Wear, National Aeronautics and Space Administration Special Publication 181, pp. 267-333, 1968.

14. Armstrong, E. L., et al, Minimizing Water-Accelerated Bearing Fatigue in Turbine/Circulating Oils, Paper 76AM-7B-4 presented at the American Society of Lubrication Engineers Meeting in Philadelphia, Pa., May 10-13, 1976.

15. Bailey, J. M. and D. Godfrey, Coefficient of Friction and Damage to Contact Area During the Early Stages of Fretting, II - Steel, Iron, Iron Oxide, and Glass Combinations, National Advisory Committee for Aeronautics, Technical Note 3144, 1954.

16. Barnes, D. and H. Woodley, Fretting Experiments Carried Out on Dragon Heat Exchanger Components (Fretting Experiments on Heat Exchanger Components of Nuclear Reactors), Atomic Energy Establishment, Winfrith, England, December 1969.

17. Barton, J. R., Bearing Steels: The Rating of Nonmetallic Inclusions, American Society for Testing and Materials, STP No. 575, pp. 189-213, 1975.

18. Bayer, R. G., et al., "Engineering Model for Wear," Wear, 5, pp. 378-391, 1962.

19. Benzing, R. J. and B. D. McConnell, "Wear Behavior of a Phenyl Methyl Silicone Bonded Solid Film Lubricant," First International Conference on Solid Lubrication, Denver, Colo., August 24-27, 1971, American Society of Lubrication Engineers Proceedings, pp. 129-142, 1971.

20. Bethune, B. and R. B. Waterhouse, "Adhesion of Metal Surfaces Under Fretting Conditions, I. Like Metals in Contact," Wear, 12, pp. 289-296, 1968.

21. Bethune, B. and R. B. Waterhouse, "Electrochemical Studies of Fretting Corrosion," Wear, 12, pp. 27-34, 1968.

22. Bilby, B. A., A. H. Cottrell, and K. H. Swinden, "The Spread of Plastic Yield for a Notch," Proceedings of the Royal Society of London, A-272, pp. 304-314, 1963.

23. Bill, R. C., Fretting of Nickel-Chromium-Aluminum Alloys at Temperatures to 816°C, National Aeronautics and Space Administration TN-D-7570, 1974.

24. Bill, R. C., Fretting of Titanium at Temperatures to 650°C in Air, National Aeronautics and Space Administration TN-D-8048, 1975.

25. Bill, R. C., Study of Fretting Wear in Titanium, Monel-400, and Cobalt - 25% Molybdenum Using Scanning Electron Microscopy, National Aeronautics and Space Administration TN-D-6660, 1972.

26. Bisson, E. E., Various Modes of Wear and Their Controlling Factors, Paper presented at the 71st Annual Meeting of the American Society for Testing and Materials, San Francisco, California, June 23-28, 1968, American Society for Testing and Materials, STP No. 446, 1969.

27. Bowers, J. E., N. J. Finch, and A. R. Goreham, "The Prevention of Fretting Fatigue in Aluminum Alloys," The Institution of Mechanical Engineers (London), Proceedings, 182, Part I, pp. 703-714, 1967-68.

28. Bramhall, R., Studies in Fretting Fatigue, Ph.D. Thesis, Oxford University, Oxford, England, 1973.

29. Broszeit, E., Model Wear Investigations Concerning the Effect of the Intermediate Medium on the Sliding Characteristics in the Case of a Contact Between Different Materials, Dr.-Ing. Dissertation, Technische Hochschule, Darmstadt, Germany, 1972.

30. Brunori, G., U. Farinelli, and G. Tomassetti, General Problems of Fretting Corrosion, Paper presented at the First National Conference on Tribology, San Donato, Milan, Italy, June 11-13, 1973, available from British Library Lending Division, Boston Spa, England, 1974.

31. Burck, L. H., C. P. Sullivan, and C. H. Wells, "Fatigue of a Glass-Bead Blasted Nickel-Base Superalloy," Metallurgical Transactions, 1, pp. 1595-1600, 1970.

32. Burton, H. M., Loft Mobile Test Assembly Fuel Fabrication, Aerojet Nuclear Company, Idaho National Engineering Laboratory, Idaho Falls, Idaho, July 1974.

33. Burwell, J. T. and C. D. Strang, "On The Empirical Law of Adhesive Wear," J. Applied Physics, 23, pp. 18-28, 1952.

34. Campbell, W. E., The Current Status of Fretting Corrosion, American Society for Testing and Materials, STP No. 144, pp. 3-23, 1953.

35. Christian, J. B. and B. D. McConnell, "The Analysis of Mechanical Variables Influencing Fretting Corrosion in Grease Lubricated Bearings," Paper presented at the 26th Annual Meeting of the American Society of Lubrication Engineers, Boston, Mass., May 3-6, 1971.

*36. Collins, J. A. "Fretting-Fatigue Damage-Factor Determination," Transactions of the American Society of Mechanical Engineers, J. Engineering for Industry, 87, Part I, pp. 298-302, 1965.

37. Collins, J. A. and T. Hagan, Investigation of Accelerated Life Prediction Techniques for Army Helicopter Components, Research Report, School of Engineering, Ohio State University, Columbus, Ohio, July 1975.

*38. Collins, J. A. and S. M. Marco, "The Effect of Stress Direction During Fretting on Subsequent Fatigue Life," Proceedings of the American Society of Testing and Materials, 64, pp. 547-560, 1964.

*39. Collins, J. A. and F. M. Tovey, "Fretting Fatigue Mechanisms and the Effect of Direction of Fretting Motion on Fatigue Strength," J. Materials, 7, pp. 460-464, 1972.

40. Cook, R. H., and R. P. Skelton, "Environment-Dependence of the Mechanical Properties of Metals at High Temperature," International Metallurgical Reviews, 19, pp. 199-222, 1974.

*41. Corton, H. T., Factors Influencing Fretting Fatigue Strength, Report No. 88, Dept. of Theoretical and Applied Mechanics, University of Illinois, Urbana, Ill., 1955.

*42. Desisto, T. S. and R. Chait, Fatigue and Fretting Fatigue of Titanium Helicopter Forgings, U. S. Army, Materials and Mechanics Research Center, Watertown, Mass., July 1975.

43. Devereux, O. F., A. J. McEvily, and R. W. Staehle, "Corrosion Fatigue Chemistry, Mechanics and Microstructure," Proceedings of the International Conference on Corrosion Fatigue, NACE-2 (National Association of Corrosion Engineers), University of Connecticut, Storrs, Conn., June 14-18, 1971.

44. Douglas, D. L., G. Thomas and W. R. Roser, "Ordering, Stacking Faults and Stress Corrosion Cracking in Austenitic Alloys," Corrosion, 20, pp. 15t-18t, 1964.

45. Dowling, N. E., "Geometry Effect and the J-Integral Approach to Elastic-Plastic Crack Growth," Crack and Fracture, Ninth National Symposium on Fracture Mechanics, American Society for Testing and Materials, STP No. 601, pp. 19-32, 1976.

*46. Duquette, D. J., "Mechanics of Fretting Fatigue Crack Initiation," Research Report, Materials Research Center, Rensselaer Polytechnic Institute, Troy, New York, 1976.

47. Dyson, B. F. and D. E. Henn, "The Effect of Room Temperature Pre-Strain on Grain Boundary Cavitation in Nimonic 80A," J. Microscopy, 97, pp. 165-170, 1973.

48. Eden, E. M., W. N. Rose and F. L. Cunningham, "The Endurance of Metals," Institution of Mechanical Engineers, London, Proceedings, pp. 839-974, 1911.

49. Endo, K. and Y. Fukada, "Role of Fatigue Wear in Metals," Proceedings, Eighth Japan Congress on Testing Materials, Kyoto, Japan, pp. 69-72, 1965.

50. Endo, K. and H. Goto, "Initiation and Propagation of Fretting Fatigue Cracks," Wear, 38, pp. 311-324, 1976.

*51. Endo, K., H. Goto, and T. Fukunaga, "Behavior of Frictional Force in Fretting Fatigue," Bulletin of the Japan Society of Mechanical Engineers, 17, pp. 647-654, 1974.

52. Endo, K., H. Goto, and T. Nakamura, "Effects of Cycle Frequency on Fretting Fatigue Life of Carbon Steel," Bulletin of the Japan Society of Mechanical Engineers, 12, pp. 1300-1308, 1969.

53. Evaluation of Wear Testing, American Society for Testing and Materials, STP No. 446, 1969.

54. Evans, A. G., "Method for Evaluating the Time-Dependent Failure Characteristics of Brittle Material--And Its Application to Polycrystalline Alumina," J. Material Science, 7, pp. 1137-1146, 1972.

55. Fein, R. S., Interdisciplinary Approach to the Lubrication of Concentrated Contacts, National Aeronautics and Space Administration SP-237, p. 489, 1970.

56. Feltner, C. E. and C. Laird, "Cyclic Stress-Strain Response of F.C.C. Metals and Alloys," Acta Metallurgica, 15, pp. 1621-1653, 1967.

57. Feng, I. M. and B. G. Rightmire, "The Mechanism of Fretting," Lubrication Engineering, 9, pp. 134-136, pp. 158-160, 1953.

58. Feng, I. M. and H. H. Uhlig, "Fretting Corrosion of Mild Steel in Air and Nitrogen," J. Applied Mechanics, 76, (American Society of Mechanical Engineers, Transactions), pp. 395-600, 1954.

*59. Fenner, A. J. and J. E. Field, "Fatigue Under Fretting Condition," Revue De Metallurgie, 55, pp. 475-485, 1958.

*60. Fenner, A. J., K. H. R. Wright, and J. Y. Mann, "Fretting Corrosion and Its Influence on Fatigue Failure," Proceedings of the International Conference on Fatigue of Metals, (The Institution of Mechanical Engineers and the American Society of Mechanical Engineers), pp. 386-393, 1956.

61. Fessler, R. R., in Proceedings of the Fifth Symposium on Line Pipe Research, American Gas Association Cat. No. L30174, W-1 - W-22, 1974.

*62. Field, J. E., Effect of Direction of Fretting on the Fretting Fatigue Strength of L65 Aluminum Alloy, Research Report NEL-120, National Engineering Laboratory, East Kilbride, Scotland, 1963.

*63. Field, J. E., "Fretting Corrosion on a Screwed Joint Under Prolonged Fatigue Loading," The Engineer, 200, London, pp. 301-302, 1955.

*64. Field, J. E., Fretting Fatigue - Ways of Preventing or Reducing, Research Report, National Engineering Laboratory, Glasgow, Scotland, July 1973.

65. Filemonov, G. N., et al., "Fatigue Strength of Heavy-Duty Surface Hardened Shafts in a Press-Fitted Joint," Soviet Materials Science, 11, pp. 266-270, 1975.

66. French, R. D., Coatings for Wear Resistance, U. S. Army, Materials and Mechanics Research Center, Watertown, Mass., July 1976.

67. French, R. D., Materials for Fretting and Wear Resistance, U.S. Army, Materials and Mechanics Research Center, Watertown, Mass., July 1976.

68. Godfrey, D., Investigation of Fretting by Microscopic Observation, National Advisory Committee for Aeronautics, Technical Note 2039, 1950.

69. Godfrey, D. and J. M. Bailey, Coefficient of Friction and Damage to Contact Area During the Early Stages of Fretting, I - Glass, Copper, or Steel Against Copper, National Advisory Committee for Aeronautics, Technical Note 3011, 1953.

70. Godfrey, D. and E. E. Bisson, "National Advisory Committee for Aeronautics Studies of Fretting (Fretting Corrosion) and Principles of Mitigation," Lubrication Engineering, 8, pp. 241-243, and p. 262, 1952.

71. Gokgol, O., Estimation of Endurance of Light Metal Alloy Lugs with Interference Fit Bushes, Royal Aircraft Establishment, Farnborough, England, 1971.

72. Golego, N., A. Ya. Alyab'ev, and V. Shevelya, Fretting Corrosion, National Aeronautics and Space Administration Technical Translation TT F-13, 953, April 1972 (from Grazhandanskaya Aviataiya, No. 1, pp. 18-19, 1971.).

73. Golego, N., A. Ya. Alyab'ev, and V. V. Shevelya, "The Role of Electrochemical Phenomena in Fretting Corrosion of Metals," Soviet Materials Science, 8, pp. 521-526, 1972.

*74. Goss, G. L. and D. W. Hoeppner, "Characterization of Fretting Fatigue Damage by SEM Analysis," Wear, 24, pp. 77-95, 1973.

*75. Goss, G. L. and D. W. Hoeppner, "Normal Load Effects in Fretting Fatigue of Titanium and Aluminum Alloy," Wear, 27, pp. 153-159, 1974.

76. Grosskreutz, J. C., Metal Fatigue Damage, American Society for Testing and Materials, STP No. 495, pp. 5-60, 1971.

77. Halliday, J. S., "Experimental Investigation of Some Processes Involved in Fretting Corrosion," Conference on Lubrication and Wear, Institution of Mechanical Engineers, Paper 39, London, pp. 640-646, 1957.

78. Halliday, J. S. and W. Hirst, "The Fretting Corrosion of Mild Steel," Proceedings of the Royal Society of London, A-236, pp. 411-425, 1956.

79. Handbook of Fatigue Testing, American Society for Testing and Materials, STP No. 566, 1973.

*80. Harris, W. J., Fretting Fatigue with Particular Reference to "Anti-Fret" Treatments, DeHavilland Div., Hawker Siddeley Aviation Ltd., Edgware, England. April 1965.

*81. Harris, W. J., Some Studies of the Mechanism of Fretting Fatigue, DeHavilland Div., Hawker Siddeley Aviation Ltd., Edgware, England, June 1966.

*82. Harris, W. J., The Influence of Fretting on Fatigue, Paper presented at the 24th Meeting of the Advisory Group for Aerospace Research and Development, Unione Industriale, Turin, Italy, April 17-26, 1967.

*83. Harris, W. J., The Influence of Fretting on Fatigue, Part 3, Rolls Royce, Ltd., Derby, England, 1972.

84. Hartley, N. E., et al., "Friction Changes in Ion-Implanted Steel," J. Materials Science, 8, pp. 900-904, 1973.

85. Hertel, H., Fatigue Strength in Construction, Technische Universitaet, Institut fuer Luft-Fahrzeugbau, Berlin, West Germany (in German), 1969.

*86. Hirakawa, K., S. Nishimura and K. Nishioka, "Fundamental Investigations of Fretting Fatigue (Part 1, On the Relative Slip Amplitude of Press-Fitted Axle Assemblies," Bulletin of the Japan Society of Mechanical Engineers, 11, pp. 437-445, 1968.

*87. Hoeppner, D. W., Fretting Fatigue and Corrosion Fatigue of Metallic Materials 12626-MS, University of Missouri, Graduate School, Columbia, Mo. July 1975 - June 1976.

*88. Hoeppner, D. W., Navy Environment - Fretting Fatigue Damage of Aircraft Structural Materials, University of Missouri, Graduate School, Columbia, Mo., July 1974.

89. Hoeppner, D. W. and G. L. Goss, "A Fretting Damage Threshold Concept," Wear, 27, pp. 61-70, 1974.

*90. Hoeppner, D. W. and G. L. Goss, "A New Apparatus for Studying Fretting Fatigue," The Review of Scientific Instruments, 42, pp. 817-821, 1971.

*91. Hoeppner, D. W. and G. L. Goss, Mechanisms of Fretting Fatigue, Lockheed-California Company, Report No. LR-24367, December 1970.

*92. Hoeppner, D. W. and G. L. Goss, "Metallographic Analysis of Fretting Fatigue in Ti-6Al-4V MA and 7075-T6 Aluminum," Wear, 27, pp. 175-187, 1974.

*93. Hoeppner, D. W. and G. L. Goss, "Research on the Mechanism of Fretting Fatigue," Proceedings of the International Conference on Corrosion Fatigue, NACE-2, Storrs, Conn., June 14-18, 1971, pp. 617-626, 1972.

*94. Hoeppner, D. W. and G. L. Goss, The Effect of Fretting Damage on the Fatigue Behavior of Metals, Lockheed-California Company, Report No. LR-25317, May 1972.

95. Horger, O. J., Influence of Fretting Corrosion on the Fatigue Strength of Fitted Members, American Society for Testing and Materials, STP No. 144, pp. 40-53, 1953.

96. Horger, O. J. and J. L. Maulbetsch, "Increasing the Fatigue Strength of Press-Fitted Axle Assemblies by Surface Rolling," Transactions of the American Society of Mechanical Engineers, 58, pp. A-91-A-98, 1936.

97. Hurricks, P. L., "The Fretting Wear of Mild Steel from Room Temperature to 200°C," Wear, 19, pp. 207-229, 1972.

98. Hurricks, P. L., "The Fretting Wear of Mild Steel from 200°C to 500°C," Wear, 30, pp. 189-212, 1974.

99. Hurricks, P. L., "The Mechanism of Fretting - A Review," Wear, 15, pp. 389-409, 1970.

100. Ivanova, V. S. and M. G. Veitsman, "The Effect of Nairit Coatings on Cyclic Strength of Samples and Parts Subject to Fretting Corrosion, Army Foreign Science and Technology Center, Charlottsville, Va., July 1974; translated from Ustalost Metal. I Spavlov, M., (USSR), pp. 103-108, 1941.

101. James, L. A., "Some Questions Regarding the Interaction of Creep and Fatigue," J. of Engineering Materials and Technology, 98, pp. 235-243, 1976.

102. Johnson, R. L., Shuttle Lubrication, Bearings and Seals, National Aeronautics and Space Administration, Lewis Research Center, Cleveland, Ohio, 1976.

103. Johnson, R. I. and M. A. Swikert, Friction and Wear Under Fretting Conditions of Materials for Use as Wire Friction Dampers of Compressor Blade Vibration, National Aeronautics and Space Administration TN-D-4630, 1968.

104. Kauger, E., "Fretting Failures," Failure Analysis and Prevention, Vol. 10, American Society of Metals Handbook, pp. 154-160, 1975.

105. Ketcham, S. J. and W. E. Mackenzie, Advanced Materials for Reduction of Aircraft Maintenance Cost and Manpower, U.S. Navy, Air Development Center, Warminster, Pa., July 1974.

106. Kimura, Y., "An Interpretation of Wear as a Fatigue Process," Proceedings of the Japan Society of Lubrication Engineers and the American Society of Lubrication Engineers Conference, Tokyo, pp. 67-75, 1976.

107. Kirschke, K., "Documentation of International Scientific and Technical Literature in the Field of Wear, Friction and Lubrication," Lubrication Engineering, pp. 362-367, 1975.

108. Krylov, K. A., "Enhancement of Wear Resistance of Aircraft Parts," Izdatel'Stvo Transport, Moscow (in Russian; 144 pages), 1974.

109. Linder, B. and T. Ericsson, Test Methods for Brake-Line Tubing, Swedish Corrosion Institute, Stockholm, July 1973.

*110. Liu, H. W., H. T. Corten and G. M. Sinclair, "Fretting Fatigue Strength of Titanium Alloy RC 130B," Proceedings of the American Society for Testing and Materials, 57, pp. 623-642, 1957.

*111. Malkin, S., D. P. Majors, and T. H. Courtney, "Surface Effects During Fretting Fatigue of Ti-6Al-4V," Wear, 22, pp. 235-244, 1972.

112. Manson, S. S., Thermal Stress and Low Cycle Fatigue, McGraw Hill, New York, 1966.

113. Manual on Fatigue Testing, American Society for Testing and Materials, STP No. 91, 1949.

113a. Manual on Low-Cycle Fatigue Testing, American Society for Testing and Materials, STP No. 465, 1970.

114. McClintock, F. A., Fracture: An Advanced Treatise (Ed. by H. Leibowitz), Vol. 3, p. 47-225, Academic Press, New York, 1971.

*115. Milestone, W. D., An Investigation of the Basic Mechanisms of Mechanical Fretting and Fretting-Fatigue at Metal-to-Metal Joints, with Emphasis on the Effects of Friction and Friction-Induced Stresses, Ph. D. Thesis, Ohio State University, Columbus, Ohio, 1966.

116. Milestone, W. D., A New Apparatus for Investigating Friction and Metal-to-Metal Contact in Fretting Joints, American Society for Testing and Materials, STP No. 462, 1970.

117. Milestone, W. D. and J. T. Janeczko, "Friction Between Steel Surfaces During Fretting," Wear, 18, pp. 29-40, 1971.

*118. Mooney, J. L., The Effect of Fretting on the Fatigue Strength of Bolted Joints, Special Problem Report, Dept. of Civil Engineering, University of Illinois, Urbana, Ill., May 1964.

119. Mueller, K., The Effect of Lubricants on Fretting Corrosion, Represented by Frictional Work and Fretting Wear, VDI-Forschungsheft, No. 564 (in German), 1974.

120. Nau, B. S. and D. Reddy, Wear Testing, British Hydromechanics Research Association, Harlow, England, 1968.

*121. Nishioka, K. and K. Hirakiwa, "Fundamental Investigations on Fretting Fatigue (Part 2, Fretting Fatigue Testing Machine and Some Test Results)," Bulletin of the Japan Society Society of Mechanical Engineers, 12, pp. 180-187, 1969.

*122. Nishioka, K. and K. Hirakawa, "Fundamental Investigations of Fretting Fatigue (Part 3, Some Phenomena and Mechanisms of Surface Cracks)," Bulletin of the Japan Society of Mechanical Engineers, 12, pp. 397-407, 1969.

*123. Nishioka, K. and K. Hirakawa, "Fundamental Investigations of Fretting Fatigue (Part 4, The Effect of Mean Stress)," Bulletin of the Japan Society of Mechanical Engineers, 12, pp. 408-414, 1969.

*124. Nishioka, K. and K. Hirakawa, "Fundamental Investigations of Fretting Fatigue (Part 5, The Effect of Relative Slip Amplitude)," Bulletin of the Japan Society of Mechanical Engineers, 12, pp. 692-697, 1969.

*125. Nishioka, K. and K. Hirakawa, "Fundamental Investigations of Fretting Fatigue (Part 6, Effects of Contact Pressure and Hardness of Materials)," Bulletin of the Japan Society of Mechanical Engineers, 15, pp. 135-144, 1972.

*126. Nishioka, K. and K. Hirakawa, "Some Further Experiments on the Fretting Fatigue Strength of Medium Carbon Steel," Mechanical Behavior of Materials, Vol. III, Temperature Effects of Metals, Environmental Effects, Polymers, The Society of Materials Science, Japan, 1972.

*127. Notes on the Influence of Fretting on Fatigue, Engineering Science Data Unit (Sponsors Royal Aeronautical Society and the Institution of Mechanical Engineers), Item No. 67012, London, June 1967.

128. Oding, I. A., and V. S. Ivanova, "Fatigue of Metals Under Contact Friction," Proceedings of the International Conference on Fatigue of Metals, The Institution of Mechanical Engineers and the American Society of Mechanical Engineers), pp. 408 - 413, 1956.

129. Ohmae, N., K. Kobayashi and T. Tankizoe, "Characteristics of Fretting of Carbon Reinforced Plastics," Wear, 29, p. 345-353, 1974.

130. Ohmae, N., T. Nakai, and T. Tsukizo, "Prevention of Fretting by Ion Plated Films," Wear, 30, pp. 299-309, 1974.

131. Ohmae, N. and T. Tsukizoe, "The Effect of Slip Amplitude on Fretting," Wear, 27, pp. 281-294, 1974.

*132. Overd, A. H., Fretting Fatigue Tests of Pin Joints, Saunders-Roe, Ltd., Report No. SR/S/1188, Great Britain, June 1958.

133. Padberg, D. J., Fretting Resistant Coatings for Titanium Alloys, Final Report, April 1972 - June 1973, McDonnell Aircraft Co., St. Louis, Mo. 1973.

134. Paris, P. C. and G. C. Sih, Fracture Toughness Testing and Its Applications, American Society for Testing and Materials, STP No. 381, pp. 30-81, 1965.

135. Paton, N. E. and J. C. Williams, in Effect of Hydrogen on Behavior of Materials (ed. by I. M. Bernstein and A. W. Thompson), Proceedings of International Conference, Moran, Wy., Sept. 7-11, 1975, The Metallurgical Society of A.I.M.E., pp. 409-431, 1976.

*136. Peterson, R. E. and A. M. Wahl, "Fatigue of Shafts at Fitted Members, with a Related Photoelastic Analysis," Transactions of the American Society of Mechanical Engineers, 57, pp. A-1 - A-11, 1935.

137. Petukhov, A. N., "Fatigue Strength of Constructional Materials and Components of GTD-Type Compressors under Condtions of Fretting Corrosion," Strength of Materials, 4, pp. 227-231, 1972.

*138. Phillips, C. E. Fretting Corrosion and Fatigue Failure, Teknisk Ukeblad, 105, p. 281, 1958.

*139. Pogoretskii, R. G., I. A. Nironovich, and I. I. Kadar, "Fatigue Failure of Steel Shafts Under Conditions of Fretting Corrosion," Soviet Materials Science, 8, pp. 5-8, 1972.

140. Rabinowicz, E., Friction and Wear of Materials, John Wiley, New York, Chapter 6, 1965.

141. Rabinowicz, E. and D. Tabor, "Metallic Transfer Between Sliding Metals, An Autoradiographic Study," Proceedings of the Royal Society, A-208, pp. 455-475, 1951.

142. Research in Zircaloy Braze Alloy Development, IIT Research Institute, Chicago, Ill., January 1 - March 31, 1968, April 1968.

143. Rhodin, R. N., Binding, Valency and Charge Transfer in Chemical Reactions of Metal Surfaces 8961-MC, Cornell University, School of Engineering, Ithaca, N. Y., July 1973.

144. Rice, J. R., "A Path Independent Integral and the Approximate Analysis of Strain Concentration by Notches and Cracks," J. of Applied Mechanics, 35, pp. 379-386, 1968.

*145. Rimbey, D. H., An Experimental Study of Fretting Corrosion and its Influence on Fatigue Strength, Thesis, School of Engineering, University of Illinois, Urbana, Ill., 1967.

*146. Roberts, G., The Effect of Contact Geometry on Fretting Fatigue, Fracture Control Program Report No. 17, College of Engineering, University of Illinois, Urbana, Ill., June 1975.

*147. Rodriguez, G. L. and H. M. Lawton, Prevention of Fretting Fatigue, Paper presented at the 28th National Forum of the American Helicopter Society, Washington, D.C., May 1972.

148. Rollins, C. J. and P. E. Sandorff, Slip Front Mechanisms in Mechanical Joints, Paper No. 71-370, American Institute of Aeronautics and Astronautics, New York, 1971.

149. Rowe, C. N. and W. R. Murphy, "Mechano-Chemistry in Tribology," National Science Foundation Tribology Workshop, Proceedings, October 1973, NTIS No. PB241253, April 1974.

150. Rozeanu, L., "Fatigue Wear as a Rate Process," Wear, 6, pp. 337-340, 1963.

*151. Ryman, R. J., and A. J. Billingham, An Investigation of the Fretting Fatigue Strength of BS L65 Aluminum Alloy Under Sinusoidal and Narrow Band Random Cyclic Stressing, Testwell Ltd., Daventry, England, 1973.

*152. Sachs, G. and O. J. Horger, "Fretting Corrosion and Fatigue," Metals Engineering: Design, Vol. 1, (ed. by O. J. Horger), American Society for Testing and Materials Handbook, Second Edition, p. 395, 1965.

153. Sachs, G. and P. Stefan, "Chafing Fatigue Strength of Some Metals and Alloys," Transactions of the American Society of Mechanical Engineers, 29, p. 373, 1941.

*154. Sandifer, J. P., "Evaluation of Methods for Reducing Fretting Fatigue Damage in 2024-T3 Aluminum Lap Joints," Wear, 26, pp. 405-412, 1973.

*155. Sandifer, J. P., Fretting Fatigue on Graphite/Epoxy Composites, Research Report, Lockheed-California Co., May 26, 1976.

156. Scaife, E. C., and P. L. James, "Influence of Environment on Intergranular Cavitation," Metal Science Journal, 2, pp. 217-220, 1968.

*157. Schofield, R. E., "A Literature Survey on Fretting and Fretting Fatigue," (Unpublished Report), Dept. of Civil Engineering, Univ. of Illinois, Urbana, Ill., June 1958.

158. Scully, J. C., in Effect of Hydrogen on Behavior of Materials (Ed. by A. W. Thompson and I. M. Bernstein), Proceedings of an Internal Conference, Moran, Wy., Sept. 7-11, 1975, The Metallurgical Society of the A. I. M. E., 1976.

159. Scully, J. C., "Stress Corrosion Cracking: Introductory Remarks," The Theory of Stress Corrosion Cracking in Metals, North Atlantic Treaty Organization, Brussels, pp. 1-16, 1971.

*160. Sinclair, G. M., G. Roberts, and H. C. Yeh, An Analysis of Critical Variables in Fretting Fatigue, Research Report, Dept. of Theoretical and Applied Mechanics, Univ. of Illinois, Urbana, Ill., July 1974.

161. Smith, J. O., and C. K. Liu, "Stresses Due to Tangential and Normal Loads on an Elastic Solid with Application to Some Contact Stress Problems," J. Applied Mechanics, 20, pp. 157-166, 1953.

162. Society of Automotive Engineers, (SAE) Fatigue Design Handbook, Advances in Engineering, Vol. 4, Warrendale, Pa., 1968.

163. Speidel, M. O., High-Temperature Materials in Gas Turbines (Ed. by P. R. Sahm and M. O. Speidel), Elsevier, Lausanne, Switzerland, pp. 207-252, 1974.

*164. Spiers, R. and S. G. Gullimore, "Fretting Fatigue Failure in Friction Grip Bolted Joints," J. Mechanical Engineering Science, 10, pp. 434-437, 1968.

165. Staehle, R. W., "Stress Corrosion Cracking of the Fe-Co-Ni Alloy System," The Theory of Stress Corrosion Cracking in Alloys, (Ed. by J. C. Scully), North Atlantic Treaty Organization, Brussels, pp. 223-286, 1971.

*166. Starkey, W. L., S. M. Marco and J. A. Collins, "Fretting-Fatigue Damage of Titanium and Steel," Machine Design, 30, p. 140, 1958.

167. Stowers, I. F. and E. Rabinowicz, , "The Mechanism of Fretting Wear," J. Lubrication Technology (Transactions, A.S.M.E.), 95F, pp. 65-70, 1973.

168. Suh, N. P., "The Delamination Theory of Wear," Wear, 25, pp. 111-124, 1973.

169. Swenson, D. O., "Discrete Dislocation Model of a Fatigue Crack Under Shear Loading - Part I," J. Applied Mechanics, 36, pp. 723-730, 1969.

170. Swikert, M. A. and R. I. Johnson, Friction and Wear Under Fretting Conditions of Materials for Use as Wire Friction Dampers of Compressor Blade Vibration, National Aeronautics and Space Administration TN-D-4630, 1968.

171. Syrett, B. C., et al., Assessment of Trip Steels for Orthopedic Implants, Stanford Research Institute, Materials Laboratory, Menlo Park, California, May 1975.

172. Taylor, D. E. and R. B. Waterhouse, "Sprayed Molybdenum Coatings as a Protection Against Fretting Fatigue," Wear, 20, pp. 401-407, 1972.

173. Tien, J. K., in Effect of Hydrogen on Behavior of Materials (Ed. by A. W. Thompson and I. M. Bernstein), Proceedings of an International Conference, Moran, Wy., Sept. 7-11, 1975, The Metallurgical Society of the A.I.M.E., 1976. pp. 309-326, 1976.

174. Tomlinson, G. A., "The Rusting of Steel Surfaces in Contact," Proceedings of the Royal Society of London, Series A115, pp. 472-484, 1927.

175. Tomlinson, G. A., P. L. Thorpe, and J. H. Gough, "An Investigation of Fretting Corrosion of Closely Fitting Surfaces," Institution of Mechanical Engineers, 141, London, Proceedings, pp. 223-249, 1939.

*176. Toth, L., "The Investigation of the Steady Stage of Fatigue Fretting," Wear, 20, p. 277-286, 1972.

177. Toth, L., "The Investigation of the Steady Stage of Metal Fretting," Acta Technica, 74, Scandanavia, pp. 197-213, 1973.

178. Tracey, D. M., "Finite Element Solutions for Crack-Tip Behavior in Small-Scale Yielding," J. Engineering Materials and Technology, 98, pp. 146-151, 1976.

179. "Tribology for the Eighties," Proceedings of the Third International Tribology Conference, Paisley, Scotland, September 22-25, 1975, Wear, 34, 1975.

180. Uhlig, H. H., "Mechanism of Fretting Corrosion," J. Applied Mechanics, 21, pp. 401-407, 1954.

181. Uhlig, H. H., W. D. Tierney and A. McClellan, Test Equipment for Evaluating Fretting Corrosion, American Society for Testing and Materials, STP No. 144, pp. 71-81, 1953.

*182. vanLeeuwen, H. P., A. Nederveen, and H. H. Ruiter, Fretting and Fatigue of Pin Loaded Lugs Under Complex Loads, The Netherlands National Aerospace Laboratory NLR TR 73127U, September 1973.

183. Vermilyea, D. A. and R. B. Diegle, "Concerning Strain-Enhanced Corrosion Mechanisms of SCC," Corrosion-NACE, 32, pp. 26-29, 1976.

*184. Warlow-Davies, E. J., "Fretting Corrosion and Fatigue Strength: Brief Results of Preliminary Experiments," Institution of Mechanical Engineers, London, Proceedings, 146, pp. 32-38, 1941.

185. Waterhouse, R. B., "Fretting Corrosion," The Institution of Mechanical Engineers, London, Proceedings, 169, pp. 1157-1172, 1955.

186. Waterhouse, R. B., "Fretting Corrosion," International Series of Monographs on Materials Science and Technology, Vol. 101, Pergamon Press, Oxford and New York, p. 265, 1972.

187. Waterhouse, R. B., Fretting Corrosion, Pergamon Press, Ltd., Headington Hill Hall, Oxford, England, 1972.

188. Waterhouse, R. B., "Fretting in Hostile Environments," Wear, 34, pp. 301-309, 1975.

189. Waterhouse, R. B., "Influence of Local Temperature Increases on the Fretting Corrosion of Mild Steel," J. Iron and Steel Institute, pp. 301-305, 1961.

190. Waterhouse, R. B., "The Effect of Clamping Stress Distribution on the Fretting Fatigue of Alpha Brass and Al-Mg-Zn Alloy," American Society of Lubrication Engineers (ASLE), Transactions, 11, pp. 1-5, 1968.

191. Waterhouse, R. B., "The Effect of Fretting Corrosion in Fatigue Crack Initiation," Proceedings of the International Conference on Corrosion Fatigue, NACE-2, Storrs, Conn., June 14-18, 1971, National Association of Corrosion Engineers, pp. 608-615, 1972.

192. Waterhouse, R. B., "The Prevention of Fretting Corrosion," Corrosion Prevention and Control, 3, pp. 37-39, 1956.

193. Waterhouse, R. B. and J. Allery, "The Effect of Powders in Petrolatum on the Adhesion Between Fretted Steel Surfaces," American Society of Lubrication Engineers (ASLE), Transactions, 9, pp. 179-185, 1966.

*194. Waterhouse, R. B., M. K. Dutta and P. J. Swallow, "Fretting Fatigue in Corrosive Environments," Mechanical Behavior of Materials, Vol. III, Temperature Effects of Metals, Environmental Effects, Polymers, The Society of Materials Science, Japan, 1972.

195. Waterhouse, R. B. and D. E. Taylor, "Fretting Debris and the Delamination Theory of Wear," Wear, 29, pp. 337-344, 1974.

*196. Waterhouse, R. B. and D. E. Taylor, "Fretting Fatigue in Steel Ropes," Lubrication Engineering, 27, pp. 123-127, 1971.

197. Waterhouse, R. B. and D. E. Taylor, "The Initiation of Fatigue Cracks in a 0.7% Carbon Steel by Fretting," Wear, 17, pp. 139-147, 1971.

198. Wei, R. P. and J. D. Landes, "Correlation Between Sustained-Load and Fatigue Crack Growth in High-Strength Steels," Materials Research and Standards, 9, pp. 25-27, 1969.

199. Wells, C. H., C. P. Sullivan and M. Gell, Metal Fatigue Damage, American Society for Testing and Materials, STP No. 495, pp. 61-122, 1971.

*200. Wharton, M. H. and R. B. Waterhouse, "The Effect of Different Contact Materials on Fretting Fatigue Strength of an Aluminum Alloy," Wear, 26, pp. 253-260, 1973.

201. What NASA/Recon Can Do For You, Scientific and Technical Information Division, Office of Technology Utilization, National Aeronautics and Space Administration, Washington, D.C., July 1970. Also: The NASA Scientific and Technical Information System - Its Scope and Coverage, NASA, Washington, D.C., March 1970.

202. Wright, G. P. and J. J. O'Connor, "Finite Element Analysis of Alternating Axial Loading of an Elastic Plate Pressed Between Two Elastic Rectangular Blocks With Finite Friction," International J. of Engineering Science, 9, pp. 555-570, 1971.

203. Wright, K. H. R., "An Investigation of Fretting Corrosion," Institution of Mechanical Engineers, London, Proceedings B, 1B, pp. 556-574, 1952/53.

204. Wright, K. H. R., "Fretting Corrosion," Corrosion Prevention and Control, 1, pp. 405-410, and pp. 465-472, 1954.

205. Wright, K. H. R., "Fretting Corrosion as an Engineering Problem," Corrosion Prevention and Control, 4, pp. 37-44, 1957.

206. Wright, K. H. R., "Fretting Corrosion of Cast Iron," Conference on Lubrication Wear, Institution of Mechanical Engineers, London, Paper 26, pp. 629-638, 1957.

207. Wright, K. H. R., Wear and Fretting Between Moving Parts, National Engineering Laboratory Report, Glasgow, Scotland, July 1973.

*208. Yeh, H. C., An Analysis of Fretting Damage on Fatigue Strength, Fracture Control Report No. 16, College of Engineering, University of Illinois, Urbana, Ill., June 1975.

*209. Yeh, H. C. and G. M. Sinclair, A Review of Fretting Fatigue, Fracture Control Program No. 8, College of Engineering, University of Illinois, Urbana, Ill., May 1973.

210. Zarkades, A. and F. R. Larson, Armor Applications of Textured Metals, Research Report, U. S. Army, Materials and Mechanics Research Center, Watertown, Mass., 1975.

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**THE NATIONAL MATERIALS ADVISORY BOARD** is a unit of the Commission on Sociotechnical Systems of the National Research Council. Organized in 1951 as the Metallurgical Advisory Board, through a series of changes and expansion of scope, it became the Materials Advisory Board and, in January 1969, the National Materials Advisory Board. In consonance with the scope of the two Academies, the general purpose of the Board is the advancement of materials science and engineering, in the national interest. The Board fulfills its purpose by: providing advice and assistance, on request, to government agencies and to private organizations on matters of materials science and technology affecting the national interest; focusing attention on the materials aspects of national problems and opportunities, both technical and nontechnical in nature, and making appropriate recommendations as to the solution of such problems and the exploitation of these opportunities; performing studies and critical analyses on materials problems of a national scope, recommending approaches to the solution of these problems, and providing continuing guidance in the implementation of resulting activities; identifying problems in the interactions of materials disciplines with other technical functions, and defining approaches for the effective utilization of materials technologies; cooperating in the development of advanced educational concepts and approaches in the materials disciplines; communicating and disseminating information on Board activities and related national concerns; promoting cooperation with and among the materials-related professional societies; maintaining an awareness of trends and significant advances in materials technology, in order to call attention to opportunities and possible roadblocks, and their implications for other fields, and recognizing and promoting the development and application of advanced concepts in materials and materials processes.